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MODELLING OF THE KINETICS OF MUNICIPAL SOLID WASTE COMPOSTING IN FULL-SCALE MECHANICAL-BIOLOGICAL TREATMENT PLANTS

A thesis submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy in Sanitary Engineering in the Faculty of Sciences and Technology of the New University of Lisbon.

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DEDICATION

"To my children, and the generations to come"

"Nature is part of our life. We grew out of the seed, the earth, and we are part of all that…
If you hurt nature you are hurting yourself."

Jiddu Krishnamurti, 1983

"What is a scientist after all? It is a curious man looking through a keyhole,
the keyhole of nature, trying to know what's going on."

Jacques-Yves Cousteau, 1971

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ABSTRACT

This work focused on the study of the kinetics of municipal solid waste composting in four full-scale mechanical-biological treatment (MBT) plants. We investigated how well the existent plants in Portugal were being operated, and estimated their performance at optimum operation. To achieve this, volatile solids (VS) content and several environmental conditions, namely temperature (T), moisture content (MC), oxygen concentration ($[O_2]$), and free air space (FAS), were monitored throughout the composting process. Experimental data was fitted with a first-order kinetic model, and a rate constant (k) that corrects for T, MC, $[O_2]$ and FAS conditions was obtained, i.e., k is characteristic of composting under optimum environmental conditions.

The kinetic model satisfactorily described the experimental data from three MBT plants. k values ranged from 0.043 d^{-1} to 0.082 d^{-1}. Modelling the fourth plant was less successful, probably due to sampling errors on the VS determinations. This is the first time that a kinetic composting model has been applied to full-scale MBT plants.

We also concluded that two of the MBT plants were poorly operated. Optimization of process management with measures of simple practical implementation was estimated to be highly significant in these poorly managed plants, increasing performance by 103% in MBT1 and 53% in MBT2. In conclusion, this work highlights the importance of having process performance monitoring and optimization programs in full-scale composting systems. It is proposed that the procedures developed here are applied for this purpose.

The composting model was further tested by applying it to data from lab- and full-scale studies collected from the literature. This is the first time that rate constants from a large set of data sources are corrected for T, MC, $[O_2]$ and FAS. k values from full-scale studies varied little, whereas those from lab-scale studies varied widely with k reaching much higher values. These observations indicate that: (i) factors other than those included in the model have a significant effect on the composting rate, as previously suggested; (ii) there is a large margin for improvement in the performance of real-scale systems; (iii) extrapolation of data from laboratory- to full-scale can be misleading and should be cautiously applied; and (iv) more studies of full-scale systems should be conducted, because these constitute an important control over laboratory-scale studies, especially when the aim is the optimization of the design, or operation, of full-scale systems.

RESUMO

Este trabalho incidiu no estudo da cinética da compostagem de resíduos sólidos urbanos (RSU) em quatro centrais de tratamento mecânico e biológico (MBT). Foi investigada a qualidade da operação das centrais existentes em Portugal e estimado o seu potencial de optimização. Para tal, monitorizou-se o teor de sólidos voláteis (VS) e as condições ambientais ao longo do processo de compostagem, nomeadamente a temperatura (T), teor de humidade (MC), concentração de oxigénio ($[O_2]$) e volume de ar disponível (FAS). Os resultados experimentais foram tratados com um modelo cinético de primeira ordem, tendo-se estimado uma constante cinética (k) corrigida para a T, MC, $[O_2]$ e o FAS, ou seja, um k característico de um processo de compostagem em condições ambientais óptimas.

O modelo cinético descreveu satisfatoriamente os dados experimentais de três centrais MBT. Os valores de k variaram entre 0,043 d^{-1} e 0,082 d^{-1}. A simulação da quarta central foi menos bem sucedida, provavelmente devido a erros de amostragem nas determinações dos VS. Esta foi a primeira vez que um modelo da cinética de compostagem foi aplicado a centrais MBT à escala real.

Quanto ao desempenho da operação, concluiu-se que esta é medíocre em duas das quatro centrais estudadas. Estimou-se que o potencial de optimização nestas duas centrais é bastante significativo, correspondendo a um aumento de desempenho de 103% na MBT1 e 53% na MBT2. Em conclusão, este trabalho demonstra claramente a importância de implementar programas de monitorização e optimização nas centrais de compostagem à escala real. Propõe-se que os procedimentos desenvolvidos aqui sejam aplicados para esse fim.

O modelo foi testado adicionalmente com dados da bibliografia para estudos às escalas laboratorial e real. Pela primeira vez, corrigiram-se para a T, MC, $[O_2]$ e FAS as constantes cinéticas de um vasto conjunto de estudos. Os valores de k dos estudos à escala real não apresentaram uma grande variação, ao passo que para a escala laboratorial a variação foi muito superior e foram atingidos k bastante mais elevados. Estes resultados indicam que: (i) outros factores que não os incluídos neste modelo têm um efeito significativo na velocidade do processo, tal como sugerido por outros autores; (ii) há uma grande margem para melhoramento do desempenho nos sistemas à escala real; (iii) a extrapolação para a escala real dos dados obtidos à escala laboratorial pode ser errónea e deve ser efectuada com as devidas precauções; e (iv) dever-se-á promover a realização de estudos à escala real, porque estes constituem um controlo importante sobre os estudos à escala laboratorial, especialmente quando o objectivo é a optimização da concepção e operação dos sistemas à escala real.

LIST OF ABBREVIATIONS

BD - total bulk density (g/cm^3, on a wet matter basis)

BVS - biodegradable volatile solids

[BVS] - biodegradable volatile solids content (either fractional, [0-1], or % - to be indicated in the text -, on a volatile solids basis)

[BVS_o] - initial biodegradable volatile solids content (either fractional, [0-1], or % - to be indicated in the text -, on a volatile solids basis)

d - day

DM - dry matter

[DM] – dry matter content (fractional, [0-1], on a wet matter basis)

FAS - free air space (fractional, [0-1])

FAS_{opt} – optimum free air space; FAS above which composting rate is maximum (fractional, [0-1])

F(FAS) - correction factor for free air space (fractional, [0-1])

F(MC) - correction factor for moisture content (fractional, [0-1])

$F(O_2)$ - correction factor for oxygen concentration (fractional, [0-1])

F(T) - correction factor for temperature (fractional, [0-1])

F(TOT) – F TOTAL (fractional, [0-1]), represents the sum of all the limitations considered herein, and is defined as the product of all the correction factors, i.e.,
$F(TOT) = F(T).F(MC).F(O_2).F(FAS)$

k – corrected first order reaction rate constant, i.e., first order reaction rate constant corrected for temperature, moisture content, oxygen concentration and free air space, base e (day^{-1})

k’ – apparent first order reaction rate constant, uncorrected by any environmental factor, base e (day^{-1})

K_{O_2} - half saturation constant (%, in volume)

MBT - mechanical-biological treatment

MBT1 - mechanical-biological treatment plant number 1 (equivalent for plants numbers 2, 3 and 4)

MC - moisture content (either fractional, [0-1], or % - to be indicated in the text -, on a wet matter basis)

MC_{opt} – optimum moisture content; moisture content above which composting rate is maximum (either fractional, [0-1], or % - to be indicated in the text -, on a wet matter basis)

MSW – municipal solid waste

NBVS - non-biodegradable volatile solids

$[O_2]$ – oxygen concentration in the free air space (%, v/v)

r - rate of degradation of biodegradable volatile solids (%/day)

RT – residence time (day)

S – substrate in the composting materials; equivalent to the biodegradable volatile solids

[S] – substrate concentration

SD- standard deviation

t - time (day)

T - temperature (ºC)

t_o – time zero, at which the composting process starts (day)

T_{max} – maximum temperature for biodegradation, above which composting rate ceases (ºC)

T_{min} – minimum temperature for biodegradation, below which composting rate ceases (ºC)

T_{opt} – optimum temperature for biodegradation, at which composting rate is maximum (ºC)

VS – volatile solids

VS consumed – VS consumed along the composting process (%, on a [VSi] basis)

[VS] – volatile solids content (either fractional, [0-1], or % - to be indicated in the text -, on a dry matter basis)

$[VS_i]$ – initial volatile solids content; it represents [VS] at time zero, at which the composting process starts (either fractional, [0-1], or % - to be indicated in the text -, on a dry matter basis)

$[VS_f]$ – final concentration of volatile solids; it represents [VS] by the end of the composting process (either fractional, [0-1], or % - to be indicated in the text -, on a dry matter basis)

GREEK LETTERS

ℓ_{ash} - particle density for the inorganic fraction (ash) (g/cm^3)

ℓ_{w} - water density (g/cm^3)

ℓ_{VS} - particle density for the volatile fraction (g/cm^3)

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1. INTRODUCTION

1.1 Biodegradable MSW: an overview

The MSW issue

Municipal solid waste (MSW) is a major issue in today's society. MSW is generated in enormous amounts, posing a threat to the environment and to public health. To make things worse, MSW generation continues to increase. Only in OECD Europe, the quantity of MSW generated per year increased 64% in the period from 1980 to 2005, from a total of 170 to 279 million tonnes/year. By 2030, the amount of MSW generated is estimated to be 400 million tonnes/year, representing an average annual increase of around 1.5%. For the developing countries, the estimated increases are even greater (OECD, 2008).

In the USA, the situation is similar, with an increase of 188% in between 1960 and 2007 from 88 to 254 million tonnes/year (USEPA, 2008).

Around the world, waste generation is very variable. In terms of kg *per* capita and year, it ranges from 210 in Central Asia and Central America to 520 in Southern Europe, 640 in Northern Europe, 650 in the USA and 690 in Oceania (IPCC, 2006). In Portugal, MSW capitation was 459 kg/year in 2006 (APA, 2008a).

The potential for MSW recycling is very high, both in terms of biodegradable and inert materials. However, most of the MSW is still disposed in landfill. In Northern and Western Europe, waste lanfilling accounts for more than 47% of MSW, in North America it is around 58%, and in Southern Europe it goes up to 85% (IPCC, 2006). In Portugal, it represented about 67% of total MSW in 2002 (Magrinho *et al.*, 2006) and 65% in 2006 (APA, 2008a).

Landfills are waste management structures which present high risks to the environment, with the potential to pollute soils, water and air (Mor *et* al., 2006; Butt *et al.*, 2008; Sharma *et al.*, 2008). The biodegradable fraction of MSW, mainly composed by food waste, paper and yard waste, is one of the most problematic when disposed to landfill, because its degradation generates high quantities of methane and leachate (Owens & Chynoweth, 1993; Kayhanian, 1995; Paxeus, 2000; Jokela *et al.*, 2002). This problem is aggravated by the fact that this is the biggest fraction of MSW. It accounts for around 54% of MSW in Europe (IPCC, 2006) and 58% in the USA (USEPA, 2008); in Portugal, the estimates go up to around 60% of a total of 4.6 million tonnes of MSW produced yearly (APA, 2009). Thus, given its weight and polluting potential, the biodegradable fraction of MSW is an important matter of concern.

Climate change - biodegradable MSW and the Kyoto protocol

There is a growing amount of evidence that climate has been changing, and there are strong suspicions that these changes have an anthropogenic cause (IPCC, 2007). The Kyoto protocol to the United Nations Framework Convention on Climate Change (UN, 1998) has established targets to limit emissions of key anthropogenic greenhouse gases for industrialised countries, with the purpose of preventing man's interference in the climate system. Strategies to achieve these targets involve, on the one hand, the reduction of emission sources for these gases and, on the other hand, the promotion of sinks for their removal (namely for carbon dioxide).

In this context, biodegradable waste management has an important role to play (Zeman & Rich, 2001; Marmo, 2008). The EU Directive on the landfill of waste (Directive 1999/31/EC), transposed to the Portuguese law by Decree-Law nr. 152/2002 of the 23rd of May 2002 will contribute to a significant reduction in methane emission from landfills. Alternative treatment methods for the biodegradable waste include composting, anaerobic digestion and incineration, which are assuming an increasing importance, especially the former ones. One of the advantages of biological treatment methods (composting and anaerobic digestion) is that organic matter is turned into a stabilised product, which can be used as a form of returning organic matter to soils. In addition to the diversion of biodegradable waste from landfills, this is another way to reduce carbon dioxide concentration in the atmosphere, the soil acting as a carbon sink (Zeman & Rich, 2001; Favoino & Hogg, 2008; Marmo, 2008).

The carbon cycle

As previously mentioned, MSW biodegradable fraction has three main components - food waste, paper and yard waste – which, as a whole, usually represent more than a half of the total. These components are thus a major issue in MSW management and, as also mentioned, a large percentage of these components, after being utilized by man and becoming a residue, is disposed in landfills. In reality, the whole process is one of concentration: food waste, paper and yard waste are actually produced in wide land extensions but, after becoming waste, these are concentrated in landfills. In their turn, landfills are waste management infrastructures specifically prepared to receive huge amounts of waste, and store it for extended time periods. In terms of the biodegradable components, and although part of the organic matter is released mainly in the form of carbon dioxide and methane, a significant part of it is retained in the landfills. These waste management practices represent a disturbance to the natural functioning of the carbon cycle. This cycle is partially interrupted, because carbon is being stored, and its return to the ecosystems is being delayed. This represents one more negative factor to the already much destabilized carbon cycle (Amundson, 2001).

Desertification of soils

In line with the rationale of the previous section, and in addition to the fact that organic matter has been harvested from wide land extensions, some of these soils have been subject to highly intensive agricultural practises. This has been taken to an extent that is causing the depletion of organic matter in the soils, potentiating erosion and desertification (Golubev, 1982; Pimentel *et al.*, 1987; Uri, 2000; Amundson, 2001; Van Oost *et al.*, 2007; Marmo, 2008). Other soils are naturally poor in organic matter.

This problem may be partly solved by returning organic matter to soils in the form of compost, provided this is not a vector of contamination by substances like heavy metals or organic pollutants. Compost, being a source of stabilized organic matter and microorganisms, has the ability to contribute to the health of soils and combat erosion and desertification problems (Gonçalves, 1999; Marmo, 2008). Portuguese soils, in this respect, are generally poor in organic matter, and hence any measures that are taken to mitigate this problem are urgent. It was estimated (Gonçalves, 2001) that the increase in the organic matter content up to 1.85% in deficient Portuguese soils would require the application of more than 116 million tonnes (dry matter) of MSW compost. This is a huge number, which illustrates well the organic matter requirement of a large part of Portuguese soils.

Biological treatment of waste and sustainability

Given the above mentioned problems associated with MSW, and biodegradable waste in particular, biological treatment of waste has a fundamental role to play.

Biological treatment is a way of diverting biodegradable waste from landfills, and thus reduce the environmental impacts of these infrastructures.

It is a means for returning organic matter into soils, especially those that are organic matter deficient. This is a valuable contribution to combat soil erosion and desertification, and make agricultural practices more sustainable. It is also a way of contributing to the normal functioning of the carbon cycle.

Promoting biological treatment of biodegradable waste is one of the measures that can effectively fight against climate changes.

As a whole, biological treatment is essential in our way towards a sustainable society. A society that is capable of looking at biodegradable residues not as waste, but as a valuable resource, making use of it as such, and reducing at the same time the environmental and public health impacts of these materials to a minimum. The new European Directive 2008/98/EC on waste is very clear on this subject.

However, notwithstanding the fact that there seems to exist a widespread consensus about these ideas at a general level, there has been for quite a long time much discussion about the way biological treatment should be applied in practice. This is especially so regarding the utilization of the output solid material in agriculture, as a function of the type of the input materials. These input materials can either be: i) biowaste, which results from the selective collection of part of the biodegradable fraction of MSW; or ii) MSW, which results from the mixed collection of the biodegradable components with other fractions, some of which have the potential to contaminate the final composted material, namely with heavy metals, but also with organic contaminants. In this respect, the trend has been towards the prohibition of the utilization of composted products obtained from the treatment of mixed MSW for agricultural purposes. At the EU level and the Portuguese national level, there are proposals for regulation by DGENV.A.2 (2001) and Gonçalves & Baptista (2000), respectively, but these have not been enforced yet.

MSW management in Portugal

Portugal has experienced considerable improvements in MSW management since the 1990's (Pássaro, 2003; Magrinho *et al.*, 2006; APA, 2008a). PERSU I (MA, 1997) is a landmark as it is considered as the first integrated strategy to tackle and improve MSW management in Portugal.

Around 340 dump sites were closed, and these MSW management infrastructures ceased to exist in 2002. Separate collection and sorting of glass, paper, cardboard, plastics and metals has been significantly reinforced. In 2008, Portugal had a total of 30276 selective collection points (representing a coverage of 301 inhabitants *per* collection point), 184 drop centres and 27 sorting plants (APA, 2008b). In terms of other MSW management infrastructures, Portugal had 34 landfills, 2 incineration plants and 77 transfer centres in 2008 (APA, 2008b).

Regarding biological treatment, this has a very important role to play in MSW management in Portugal. Due to the stringency of the present legislation framework, there is a great pressure to adequately treat the biodegradable fraction of MSW. Portugal has decided for two options, incineration and biological treatment. As far as this work is concerned, the focus will be on the biological treatment option.

In 2008, there were 9 biological treatment plants operating, representing a total treatment capacity equivalent to around 10% of the MSW generated in Portugal. However, in order to meet the requirements of the EU Directive on the landfill of waste (Directive 1999/31/EC), a national plan, consisting on ENRRUBDA (MCOTA, 2003) and PERSU II (MA, 2007) was put into action, so that 4 more plants were in construction in 2008 and 12 new plants are

planned for the near future. This makes up a total of 25 biological treatment plants (APA, 2008b), where composting will play a role, either as the only biological treatment method or after anaerobic digestion of the waste (Silveira *et al.*, 2008).

Biological treatment plants

There are several types of biological treatment plants which can be used for the treatment of MSW. Regarding the type of biological process itself, this can be based on composting, on anaerobic digestion, or both, in which case the first treatment is usually anaerobic and the second is aerobic (composting). As far as the input material is concerned, this can either come from selective collection (biowaste) or from mixed collection (MSW).

Mechanical-biological treatment (MBT) plants, which are the object of study in this work, are devoted to the treatment of mixed MSW, and include a combination of mechanical and other physical processes with biological processes. In addition to the separation and stabilization of the biodegradable fraction of waste, MBT plants frequently include the separation of useful waste materials for recycling, such as paper and cardboard, plastics or metals, as well as refuse derived fuel (RDF), which is used for energy recovery (Biala & Muller, 2001; Soyez & Plickert, 2002; Fricke *et al.*, 2005; Kuehle-Weidemeier, 2005).

The general scheme of a MBT plant is shown in figure 1.1.

MSW enters the MBT plant and is unloaded in a waste reception structure. At this stage, large waste objects may eventually be removed manually, in order to avoid mechanical problems in the subsequent stages. Waste is then subject to a pre-treatment stage, where treatment processes are mainly physical, and include materials separation, size reduction and mixing operations. The processes are mostly mechanical, but also manual, namely in the case of hand sorting of materials for recycling. Biological processes may be present at this stage, as is the case when rotary drums are used. This stage aims to: i) concentrate biodegradable matter as much as possible in a fraction for biological treatment; eventually condition this fraction (size reduction, mixing with a bulking agent); ii) separate materials for recycling (paper and cardboard, plastics or metals); iii) separate non-biodegradable materials; a high calorific value fraction is produced, which may eventually be used as RDF (refuse derived fuel).

The biological treatment stage may either be anaerobic, aerobic, or include both processes. In the case of anaerobic digestion, the fraction rich in biodegradable matter is closed in a reactor, in order to keep oxygen out of the system and to capture the biogas which is released. Heat may be supplied to maintain process temperatures at a certain pre-defined value. Water addition and mixing of the digesting waste is normally present. The outputs of the process are mainly biogas, a gas rich in methane which can be used for energy and / or heat production,

and the digested waste. The latter is normally subject to a composting stage, after a moisture removal step, and sometimes after conditioning the material with a bulking waste, in order to improve its structure.

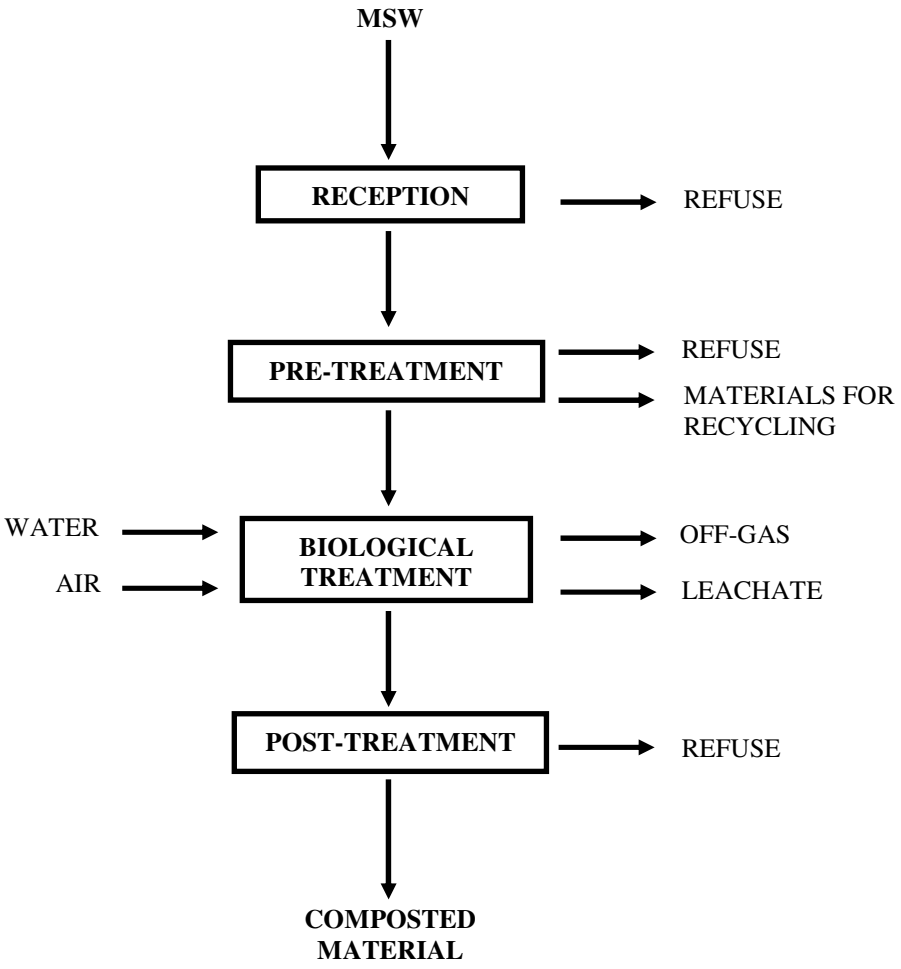

Figure 1.1. Schematic diagram of a MBT plant.

Composting may be carried out in a variety of equipments. Forced aeration is normally used, in order to maintain process temperatures and oxygen concentration in favourable ranges. Process temperature should be defined as a result of a trade-off in between maximization of process rate and material sanitization. Water is, or should be, normally supplied in order to keep moisture levels out of limiting ranges for the microbial community. Material turning is also carried, to a greater or lesser extent. Turning is a powerful means of reducing systems' heterogeneities, promoting the colonization of yet uncolonized materials, and to a certain extent reducing particle size. Process gas is normally extracted and treated, as smells are one of the major negative impacts of composting plants, and therefore adequate off-gas treatment is essential for good public acceptance. Leachate is also normally produced, which can either

be reused in the process for raising moisture levels, or subject to further treatment and discharge.

Regarding the stabilised fraction of biodegradable MSW, which results from the biological process in MBT plants, this is in some countries applied to the soil, for agricultural purposes, as it is in Portugal. However, in other countries, this utilization is forbidden, the alternative destinies being landfilling, incineration or sometimes the application to soils without agricultural uses (Biala & Muller, 2001; Soyez & Plickert, 2002; Kuehle-Weidemeier, 2005). When the final route is soil application, the composted materials are normally subject to post-treatment, which aims at removing contaminant materials. Mechanical separation processes are used at this stage. Grinding may also be performed, to reduce particle size of the compost and improve its aesthetical properties.

The specific diagrams of the MBT plants studied here are presented in section 3. The focus was on the composting processes of the plants under study. The mechanical treatment carried out in these plants is out of the scope of this work, and was dealt with by Morvan *et al.* (2002, 2003) for MBT plants numbers 1 and 2, respectively.

1.2 Topic relevance

Biological treatment plants have large associated investment and operating costs. Besides, they have impacts on the environment and surrounding populations, especially if their design and operation are poor (Bidlingmaier, 1996; Fisher, 1996; de Bertoldi, 1999; Soyez & Plickert, 2002; Fricke *et al.*, 2005; Amlinger *et al.*, 2008). Therefore, it is desirable that the operation of these plants is optimized, in order to:

- Reduce emissions and the impact on the surrounding environment, ecosystems and populations;
- Optimize costs;
- Recover and recycle as much waste as possible;
- Produce stabilized compost.

This was actually the starting point of this work. Being a subject of such an amount of investment by the Portuguese governments for the future, it was felt that it was important to know how well the existent biological treatment plants were being operated, and up to where they could get if optimised.

At the time of this study (2002-2003), Portugal had four mechanical-biological treatment plants operating. A fifth plant had been operating since the 1970's, but was inactive at the time of this study, because a new plant was under construction in order to replace the old one. Therefore, this work is about those four mechanical-biological treatment plants. No biowaste

treatment plant was studied here, but the reason was merely the inexistence of such plants in Portugal at the time.

1.3 Objectives

This work had two major objectives, which were:

- Making a diagnosis about how well the Portuguese MBT plants existent at the time of this study were being operated;
- Estimating the performance of these plants in optimized operation conditions.

A model describing the kinetics of the composting process in these plants was used as a tool, which aided in the interpretation of the experimental data and on the evaluation of the potential for optimization of the plants.

The detailed methodology adopted in this study is described in section 1.4.

1.4 Methodology

In order to achieve the global objectives indicated in section 1.3, a number of actions were planned. These were the following:

1. Definition of a simulation model to describe the kinetics of the composting process, based on the models and information available in the literature.
2. Development and implementation of an expeditious procedure for collection of experimental data from the MBT plants under study, to feed the simulation model.
3. Testing for the adequacy of the simulation model to describe the experimental data collected and estimation of k (corrected first-order rate constant).
4. Identification of the most influential model parameters in k estimation.
5. Diagnosis of the conditions at which the MBT plants under study are operating, at the level of the composting process.
6. Evaluation of the potential for optimization in the performance of the plants.
7. Application of the model to data collected from the bibliography, both for full- and lab-scale studies.

The relationship between these actions is schematized in figure 1.2.

It should be mentioned that the procedures for experimental data collection (action 2) were developed trying to make them as simple, and at the same time, as reliable as possible. With this in mind, the development of a procedure that could be implemented by the plant operators was attempted.

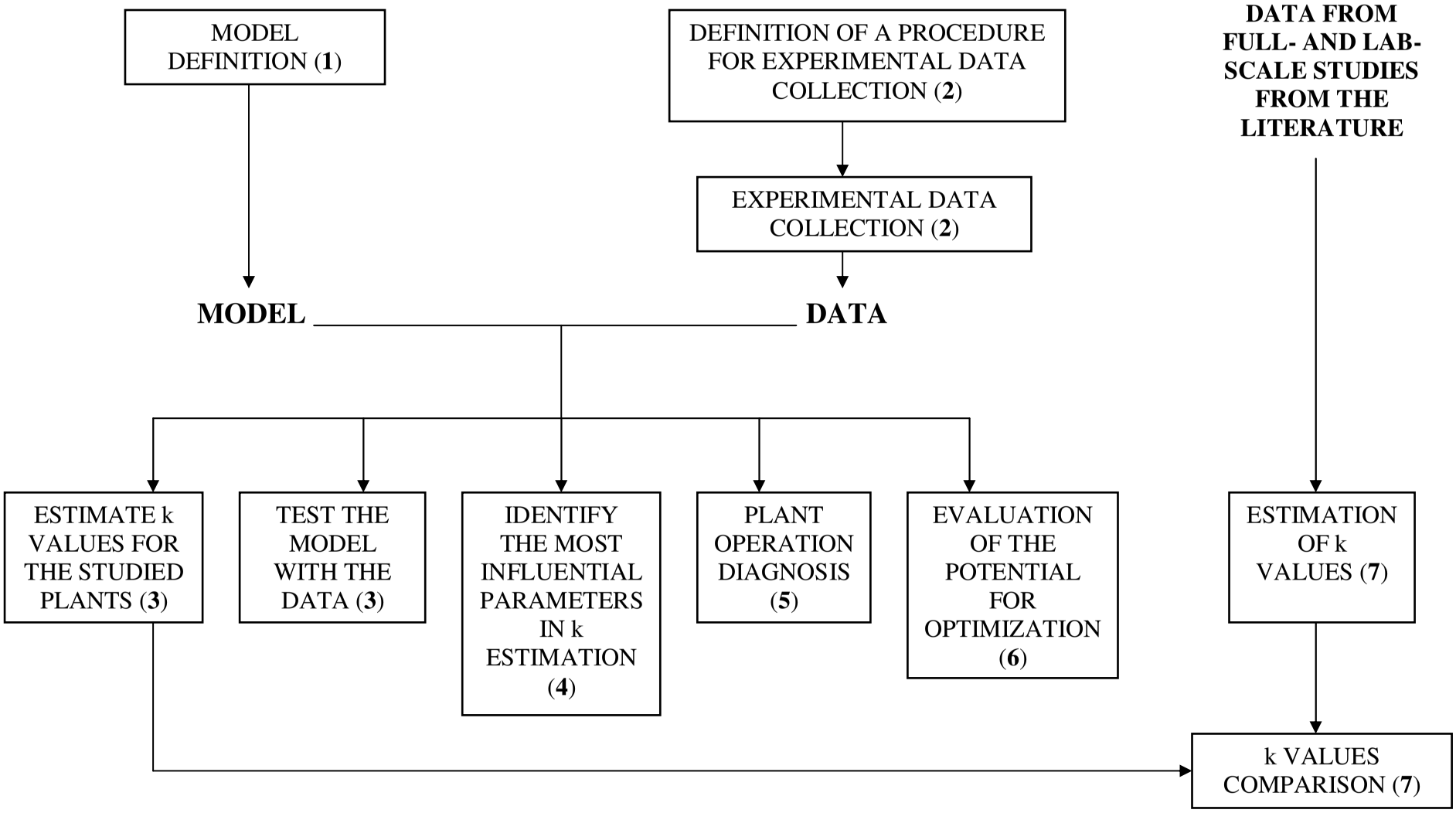

Figure 1.2. Actions planned in this work schematized. Numbers correspond to the actions defined in the present section.

1.5 Structure of the thesis

This thesis is organized as follows:

- Chapter 1 (this chapter) presents an overview about the biodegradable fraction of MSW and the topic relevance of this work. It also presents the objectives defined for this study, as well as the methodology used to achieve those objectives;
- Chapter 2 starts with basic information about the composting process. The results of the bibliographic survey on composting modelling are then presented. Based on the information found, a composting kinetics simulation model is defined and presented;
- Chapter 3 describes the case studies of this work, i.e., the four full scale MBT plants which were studied;
- In chapter 4, the materials and methods used to carry out the experimental and the simulation work are described;
- Chapter 5 is about the presentation and discussion of the results obtained. It starts with the experimental results, and proceeds with the simulation results. The latter include: fitting of the model to the experimental data; analysis of sensitivity to identify the most influential model parameters in k estimation; diagnosis of the composting operation performance in the studied plants; evaluation of the potential and targets for optimization; and comparison of the k estimates from this work with those obtained from data collected in the literature, both for lab- and for full-scale studies;
- In chapter 6, a general discussion of the results obtained is made;
- Chapter 7 is about the conclusions taken in this work;
- Chapter 8 presents recommendations for future work;
- Next, the references used from the literature are listed;
- Lastly, appendix A presents the raw experimental data collected in the studied MBT plants.

2. MODEL DEFINITION

The first action of this work was to define a simulation model to describe the kinetics of the composting process, based on the models and information available in the literature. This chapter starts with general information about the composting process (section 2.1) and then proceeds to the model definition (section 2.2).

2.1 Composting

2.1.1 Definition of composting

There are many definitions of the composting process available in the literature. The one chosen to present here is the one by Finstein & Hogan (1993):

"In composting, a solid-phase organic material serves as physical support, gas exchange matrix, source of organic and inorganic nutrients, water, and diverse indigenous microbes, a sink for metabolic waste products, and thermal insulation. The major form of microbial metabolism is aerobic respiration. One of the metabolic wastes, heat, tends to be retained within the matrix, causing self-heating, or a temperature elevation, which is characteristic of the process. Composting is useful in waste management because it can rapidly transform putrescible material to a process residue that is stabilized, storable, transportable, and possibly usable as a compost."

The composting process can be schematised as in figure 2.1.

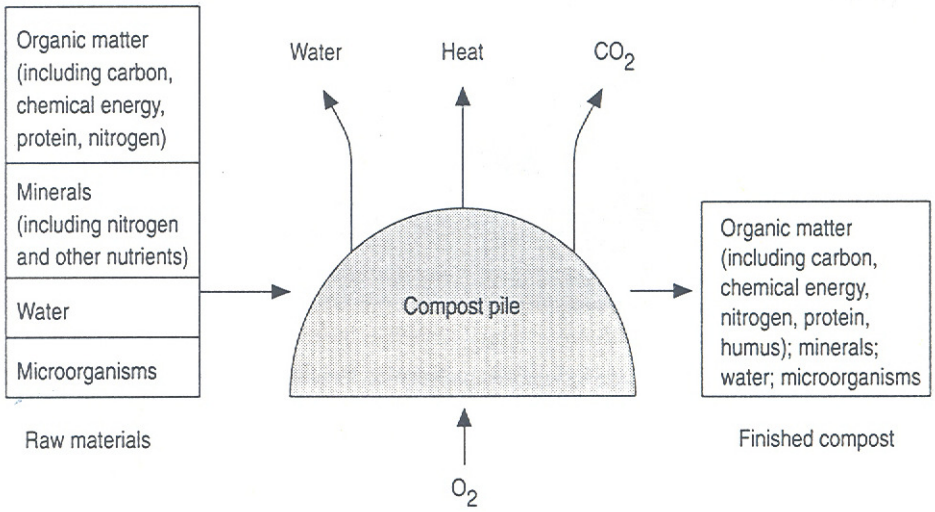

Figure 2.1. Schematic representation of the composting process (Rynk *et al.*, 1992).

2.1.2 Brief history of composting

Composting is one of the most ancient agricultural arts (Golueke, 1972). Its origins are lost in antiquity, some of the earliest recorded references to this practice being found in the bible (Poincelot, 1974).

For many centuries, farmers and gardeners have practiced composting in some of its primitive forms. Materials like night-soil, vegetable matter, animal manure, refuse, etc., were placed in piles or pits located in convenient places and allowed to decompose as conditions would permit. The process would continue until the material was ready for the soil or the farmers were ready to apply it in land. It involved little or no control, and required long periods to provide good "humus" (Gootas, 1956).

The beginning of the modern era of composting is normally attributed to the work of Sir Albert Howard, a British economic botanist employed by the Indian Government from 1905 to 1934. During this period, Sir Howard developed what he called the Indore method of composting, named after the state in central India where it was first formulated (Gray *et al.*, 1973; Poincelot, 1974; Haug, 1993).

The Indore method was first developed using only animal manure, but later it involved stacking alternate layers of readily putrescible materials such as night-soil, animal manure, sewage sludge and garbage, and relatively stable organic matter, such as straw, leaves and municipal refuse. The material was stocked to a height of about 1.5 m or was placed in pits of around 0.6-0.9 m deep. Material was turned only twice during the composting period of around six months or longer, and the leachate draining from the pile was recirculated to moisten the pile or was added to other, drier piles (Gootas, 1956).

The modern era of composting is therefore less than one century old. However, since Sir Howard's work the composting process has received considerable attention, with a consequent increase in the understanding of the composting process and in its real-scale applications. Regarding the latter, a considerable effort towards mechanization of the composting process was started in the 1920's, especially in Europe. A variety of mechanical devices were designed and patented by then. Some of these early devices were intended to improve the aesthetics of the process by enclosing it, while others were developed hopefully to speed up the process (Golueke, 1972). From these early times until now, there was a great evolution, not only in the variety of composting systems and their efficiency (Haug, 1993), but also in the number of full-scale plants. Composting has been applied at a large scale to a wide range of materials, from MSW, biowaste and sewage sludge to yard waste, industrial sludge and manures, in many countries worldwide. This trajectory has not been a simple one,

though, with numerous examples of plants closing down due to malfunctioning and odour production (Gootas, 1956; Golueke, 1972; Haug, 1993; Golueke & Diaz, 1996).

Nevertheless, the future is bright, as there is an increasing number of successful composting plants. At the EU level in particular, the future is very promising, as the Landfill Directive (1999/31/EC) created a huge opportunity for the development of the biological treatment industry (Biala & Muller, 2001; Heermann, 2003; Kuehle-Weidemeier, 2005). Portugal is a good example, with a notorious increase in the number of operating and planned biological treatment plants that has been occurring since the 1990's (section 1.1). In these plants, composting is either the sole biological treatment method or is used after anaerobic digestion, the latter option representing the tendency since the last few years.

2.1.3 The microbiology of composting

It has long been known that composting is primarily a microbiological process. If one has the chance to read the work by Waksman *et al.* (1939), most likely he will get impressed with the amount of knowledge about the microbiology of the process that already existed by that time.

The understanding that composting is, above all, a microbiological process, is of paramount importance, since this is actually the basis for good process management (Finstein, 1980; de Bertoldi *et al.*, 1983; Golueke, 1991). This was one of the strongest basis for the development of the Rutgers system of composting (Finstein, 1980), where process rate is controlled by maintenance of an appropriate process temperature by forced aeration, and it has been one of the guiding principles in most of the composting systems available nowadays.

Although small animals like earthworms or small insects can be found in composting, most of the organic matter degradation is carried out by microbes. There are three main groups of microbes involved – bacteria, fungi and actinomycetes – which may be facultative or strict aerobic (Huang *et al.*, 2000), and which have individual preferential substrates and environmental conditions for growth. There is abundant information about this topic in the literature (Waksman *et al.*, 1939; Gray *et al.*, 1971a; Gray & Bidlestone, 1973; Poincelot, 1974; Finstein *et al.*, 1980; de Bertoldi *et al.*, 1983; Golueke, 1991; Haug, 1993).

The materials subject to composting normally contain an indigenous mixed population of microorganisms derived from the atmosphere, water or soil (Gray & Bidlestone, 1973). Once materials are piled for composting, feeding of this microbiological population on the substrates leads to the production of heat and its accumulation in the pile, causing process temperature to rise (Finstein *et al.*, 1987a; Rynk *et al.*, 1992). Microbial activity and the resulting heat generation trigger a change in the environmental conditions and substrate composition along process time, which in turn causes a succession of mixed microbial

populations to occur (Waksman *et al.*, 1939; Gray & Bidlestone, 1973; Silveira, 1999; Tiquia *et al.*, 2002; Nakasaki *et al.*, 2005, 2009; Klammer *et al.*, 2008; Chroni *et al.*, 2009).

Microbial populations can be subdivided by the temperature ranges of their activity: i) psychrophiles, preferring temperatures below 20ºC; ii) mesophiles, for a temperature range in between 20ºC and 40ºC; and iii) thermophiles, above 40ºC (Gray & Bidlestone, 1973).

The following section (2.1.4) deals with the factors that are important for the composting process, and that should be subject to control, in order to optimise the composting process. In reality, once composting is primarily a microbiological process, those factors are the ones that most influence the composting microbial community.

2.1.4 Factors affecting the composting process

2.1.4.1 Temperature

Temperature is a central environmental factor in composting, being at the same time a result and a conditioning factor of the process. As previously discussed, materials for composting are normally close to ambient temperature, but once piled, heat generated by microbial activity causes the pile temperature to rise. This, in turn, causes microbial activity to increase, which increases temperature even further. This is a positive feedback loop process, in which a fast temperature rise occurs, provided favourable conditions for microbial activity, concerning other factors, are gathered (sections 2.1.4.2-2.1.4.9). However, temperature eventually gets to a point above which microbial activity starts to decrease. This optimal temperature has for long been a subject of much debate, and it is variable according to the composition of the composting material. For MSW, biowaste and other similar materials, it is thought to lie somewhere in the range of 50 to 60ºC (please see also table 2.4). Above this range, microbial activity then starts to be inhibited, and eventually ceases at around 70ºC to 80ºC (Waksman *et al.*, 1939; Gray *et al.*, 1971a; Gray & Biddlestone, 1973; Jeris & Regan, 1973a; Suler & Finstein, 1977; de Bertoldi *et al.*, 1983; Kuter *et al.*, 1985; Nakasaki *et al.*, 1985; Miller *et al.*, 1989; Golueke, 1991; Rynk *et al.*, 1992; Finstein & Hogan, 1993; Richard & Walker, 1999, 2006).

Given this, it follows that temperature is one of the most important factors to control in composting operations. Maintenance of temperature in an optimum range is crucial to achieve high organic matter stabilization rates; too low or too high temperatures will slow down the process and therefore compromise the global aim of the use of composting as a tool for organic matter stabilization and stable compost production. Furthermore, maintenance of temperature above certain levels (55-60ºC) for a certain time period is normally required in order to ensure good sanitation of the composting material (Gootas, 1956; Golueke, 1972;

Finstein *et al.*, 1987b; Haug, 1980, 1993). Therefore, a good compromise between organic matter stabilization and material sanitation can be achieved if temperatures are maintained in the 55 - 60ºC range.

Temperature control is normally done by forced aeration, but can also be controlled by pile size and configuration, especially in systems without forced aeration. It should be noted that, in normal conditions, temperature control by means of forced aeration results in oxygen control as well, as more air is required to remove a given amount of heat than to replenish the oxygen consumed by its generation (Finstein *et al.*, 1987a).

Lastly, it should be mentioned that temperature gradients always exist in the composting piles, but their nature is variable according to the type of composting system (Finstein *et al.*, 1986b; Das & Keener, 1997; Bari & Koenig, 2000; Mason, 2009)

2.1.4.2 Oxygen

As microbial metabolism in composting is aerobic, air supply and maintenance of appropriate oxygen levels in the free air space of the pile are major considerations. Low levels of molecular oxygen will slow down process rate and favour anaerobic in relation to aerobic metabolism, changing the global process to a direction in which composting systems are normally not able to cope with, namely the production of nuisance odours and polluting gases. The atmospheric concentration of O_2 is around 20.95% (v/v), and ideally it should be kept above 5-10% in the free air space of the composting material (Schulze, 1962; Suler & Finstein, 1977; Finsten *et al.*, 1987b; Nakasaki *et al.*, 1987, 1990, 1992b; de Bertoldi *et al.*, 1988; Tseng *et al.*, 1995; Michel & Reddy, 1998; Richard & Walker, 1999; Beck-Friis *et al.*, 2003; Richard *et al.*, 2006). The need to supply oxygen to the composting microbial community was on the basis for the development of the Beltsville system for composting (Epstein *et al.*, 1976).

Air supply is, like temperature, very often accomplished and controlled by the use of forced aeration in the composting systems. Pile size and shape can aid in the control of the oxygen supply, especially when forced aeration is not used. The use of bulking agents to condition the initial composting material can also be an approach, as they help in building a more favourable structure for air circulation through the composting mix (Haug, 1993).

2.1.4.3 Moisture content

Water is essential for the organic matter decomposition process, as most of the decomposition occurs in thin liquid films on the surfaces of particles (Nakasaki *et al.*, 1987; Hamelers, 2001). The theoretical optimum moisture content in composting is 100% (Golueke, 1972), because

under such conditions there would be no moisture limitations to the process. However, in practice, too high moisture levels will not allow the maintenance of appropriate levels of oxygen, due to the low diffusion coefficient of oxygen in water. Therefore, moisture contents must be such that it enables the achievement of a balance between organic matter decomposition and air renovation in the pile. Because different materials have different structures and water holding capacities, no exact generalization can be made about optimal starting or time course moisture levels. For the organic fraction of MSW and for biowaste, these values should lie in the 50 - 65% range (please see also table 2.7) (Schulze, 1961; Gray *et al.*, 1971b; Gray & Bidlestone, 1973; Jeris & Regan, 1973b; Suler & Finstein, 1977; Finstein *et al.*, 1987b; Murwira *et al.*, 1990; Nakasaki *et al.*, 1994; Richard *et al.*, 2002).

Water control can be accomplished by water addition, which should ideally be carried out during turning operations. Other factors, like aeration (both the amount of air and the type of aeration – positive or negative), also have a role on moisture control, but to a lesser extent (Haug, 1993).

One further constraint that must be considered in the management of moisture levels in composting is the post-treatment of compost, which should be carried out at relatively low levels, generally at 25 - 35%, in order to achieve good equipment performances. As a consequence, moisture levels should be decreased by the end of the process, when post-treatment steps exist.

2.1.4.4 Free air space

The composting matrix is formed by a set of particles of varying sizes, with interstices between them. The free air space (FAS) is defined as the ratio of gas volume to total volume of the composting material, and it is important in determining the total quantity and movement of air through the mixture. FAS in a composting matrix is dependent on the size of the particles and on the moisture content of the mixture. As pointed out in section 2.1.4.2, aerobic metabolism requires the maintenance of minimum levels of oxygen in the free air space of the pile. On the other hand, microbial activity is also dependent on the moisture content of the material (section 2.1.4.3). Therefore, in order to fulfil the oxygen and water requirements of the microbial population, a balance has to be achieved between the FAS and the moisture content for each particular mixture. If the water content is increased too much, FAS will become too small and lead to oxygen supply deficiencies; inversely, if water content is decreased too much, FAS may be appropriate for a good oxygen supply but there will be microbial activity limitations due to lack of water. FAS should be maintained above 30%, in

order to warrant the basis for a good oxygen supply (Schulze, 1962; Jeris & Regan, 1973b; Haug, 1993; Agnew & Leonard, 2003; Richard *et al.*, 2004; Albuquerque *et al.*, 2008).

2.1.4.5 Organic matter composition

The composition of organic matter strongly influences the composting process, as it is central in determining: i) substrate biodegradability, i.e., the total amount of organic matter that is biodegradable, in the time scale of the process; ii) reaction rate, that is, the speed at which organic matter is degraded. Organic matter has been characterised with varying classes in the composting research, but frequently solubility has been one of the criteria used for classification. Examples of organic matter classifications are: i) water soluble organic matter, hemicelluloses, cellulose, lignin and water insoluble protein (Waksman *et al.*, 1939), or ii) carbohydrates, proteins, lipids, hemicellulose, cellulose, lignin and inert organic material (Sole-Mauri *et al.*, 2007). The biodegradability and availability of the several organic matter components is variable, the soluble components being normally more rapidly degraded than the insoluble ones. Of the insoluble components, lignin has been subject to considerable attention (Kirk and Farrell, 1987; Tuomela *et al.*, 2000), because it is particularly difficult to degrade. For those substrates which lack a sufficient amount of readily available organic matter, feed conditioning may be necessary, in which substrates rich in readily available organic matter are added (Gray & Biddlestone, 1973; Poincelot, 1974; Haug, 1993; Atkinson & Jones, 1996; Kaiser, 1996; Komilis & Ham, 2003; Tremier *et al.*, 2005).

2.1.4.6 Particle size

Mechanical size reduction is often necessary in composting. Theoretically, the smaller the particle size the higher the degradation rates as the surface area available for microbial action is increased (Nakasaki *et al.*, 1987; Hamelers, 2001). However, if the particles are too small, gas exchanges are more difficult, which means that size reduction should be critically evaluated (Hamelers & Richard, 2001). When materials with small particle sizes are composted, bulking agents such as straw or wood chips are often added to maintain good porosity (Gray *et al.*, 1971b; Gray & Biddlestone, 1973; Jeris & Regan, 1973b; de Bertoldi *et al.*, 1983; Rynk *et al.*, 1992).

2.1.4.7 pH

Although materials with a high range of pH (from 3 to 11) can be composted, optimum values are between 5.5 and 8. In the beginning of the process, pH normally drops to acid values, but this drop is transitory and the system is generally capable of self-regulation. Actually, the

composting system has a very good pH buffering capacity, as both a weak acid (CO_2) and a weak base (NH_3) are produced in the degradation processes. Therefore, pH is normally not a subject of attention and control (Gray *et al.*, 1971b; Jeris & Regan, 1973c; de Bertoldi *et al.*, 1983; Golueke, 1991; Nakasaki *et al.*, 1993).

2.1.4.8 C/N ratio

Since micro-organisms utilize about 30 parts of carbon for 1 part of nitrogen, the theoretical optimum of C/N ratio should be 30:1 for any composting mass (Poincelot, 1974). However, due to the microbial availability of both nitrogen and carbon, optimal ratios have been found to vary considerably, when based on total carbon and total nitrogen determinations (Kayhanian & Tchobanoglous, 1992).

C/N ratios of around 25-35 are normally advisable, but good results have been obtained with values out of this range. In general, at higher C/N ratios the composting process is thought to be delayed through lack of nitrogen, whereas smaller C/N ratios lead to excessive nitrogen losses and eventually to microbial toxicity due to high levels of ammonium. Mixing of different materials is commonly necessary to achieve adequate C/N ratios for composting. Along the composting process, a decrease in the C/N ratio occurs, due to the loss of carbon in the form of carbon dioxide, which is normally higher than the nitrogen losses (Gootas, 1956; Gray *et al.*, 1971b; Golueke, 1972, 1991; Gray & Biddlestone, 1973; Jeris & Regan, 1973c; de Bertoldi *et al.*, 1983; Silveira, 1987; Nakasaki *et al.*, 1992a; Rynk *et al.*, 1992; Haug, 1993).

2.1.4.9 Nutrients

The microorganisms that carry out the composting process require a variety of nutrients for their growth. Nutrients can be classified according to the amounts in which they are needed by microbes. Macronutrients are those which are required in large amounts, the principal macronutrients being carbon, nitrogen, phosphorus and potassium. Micronutrients, or trace elements, are those needed in small amounts, like, for example, sulphur, calcium, magnesium or sodium. In composting, the most common nutrient limitations are caused by nitrogen, as pointed out in section 2.1.4.8 (Gray & Biddlestone, 1973; Jeris & Regan, 1973c; Poincelot, 1974; Golueke, 1991; Haug, 1993).

2.1.4.10 Inoculation

Since composting is a microbiological process, process rate is dependent on the microbial concentration present in the system (Haug, 1993). Besides, once the degradation process

commences, reproduction can be very fast, such that one single bacteria can multiply to the order of 10^7 within 24 hours (Gray & Biddlestone, 1973). Therefore, there has been a long debate on whether substrate inoculation is of any utility in speeding up the process, but there seems to be no consensus on the subject. In sterilized substrates, though, this operation may sometimes be necessary (Gray *et al.*, 1971a; Golueke, 1972; Gray & Biddlestone, 1973; Jeris & Regan, 1973b; Nakasaki & Akiyama, 1988; Golueke & Diaz, 1991; Haug, 1993; Barrena *et al.*, 2006).

2.1.4.11 Material turning

The turning operations represent favourable events in the composting process, as these contribute effectively for particle size reduction and for a wider substrate colonisation by the microbial populations responsible for substrate consumption. These operations also contribute to the homogenisation of the environmental conditions in the pile, and constitute an opportunity for material redistribution, whereby substrates in process unfavourable regions of the pile are eventually displaced to more favourable areas. On the other hand, too much agitation can lead to excessive loss of heat and moisture from the pile, but normally it is not taken to an extent where these losses are problematic (Gray *et al.*, 1971b; Gray & Biddlestone, 1973; Haug, 1993).

2.1.5 Composting kinetics

Kinetics is the study of rates of reactions. Composting kinetics in particular deals with the rate of the composting process, that is, the velocity at which biodegradable matter in the composting materials is consumed. Evaluation of this process rate can be made using several monitoring parameters, like evolution of VS or DM contents, or O_2 consumption or CO_2 emission rates (Waksman *et al.*, 1939; Schulze, 1960; Gray *et al.*, 1971b; Jeris & Regan, 1973a; Clark *et al.*, 1978; Silveira, 1999; Gea *et al.*, 2004).

There are different process management options in composting (Finstein *et al.*, 1986b; Golueke *et al.*, 1987; Lopez-Real & Vere, 1992; Finstein, 1992), but in most of them maximization of the decomposition rate is one of the main objectives. Therefore, kinetics is an important issue in the study of a composting plant and its optimization.

The composting rate has been described by several forms of kinetic equations (please see also table 2.1), namely:

- *First-order* (Haug, 1993):

$$r = \frac{d[S]}{dt} = -k.[S] \quad (2.1)$$

where r is the reaction rate, which corresponds to the consumption rate of substrate S, i.e., the biodegradable matter; [S] is the concentration of substrate S; k is the first-order rate constant.

- *n^{th}-order* (Petric & Selimbasic, 2008):

$$r = \frac{d[S]}{dt} = -k.[S]^{n} \quad (2.2)$$

where r and [S] are defined as for equation 2.1; k is the n-order kinetic constant; n is the reaction order.

If n equals 1, equation 2.2 becomes equation 2.1, i.e., the first-order reaction rate equation.

- *Monod* (Haug, 1993):

$$r = \frac{d[S]}{dt} = -\frac{k_m.[S].X}{K_s + [S]} \quad (2.3)$$

where r and [S] are defined as for equation 2.1; X is the concentration of microbes; k_m is the maximum rate of substrate utilization at high substrate concentration; K_s is the half-velocity coefficient.

- *Contois* (Bongochgetsakul & Ishida, 2008):

$$r = \frac{d[S]}{dt} = -\frac{[S]}{K_C.X + [S]} \quad (2.4)$$

where r and [S] are defined as for equation 2.1, and X as for equation 2.3; k_c is the Contois constant.

- *Gompertz* (Mason, 2008a)

The Gompertz equation has been widely used for describing microbial growth of pure cultures at constant temperature, in the following form:

$$y = \ln\frac{N}{N_o} = a \times e^{(-e^{(b - c \times t)})} \quad (2.5)$$

where N is the number of bacterial cells at time t; N_o is the number of bacterial cells at time zero; t is time; a, b and c are empirical constants. This equation has been modified and adopted to composting modelling by several authors (cf. table 2.1).

First-order kinetics was used in this work. The reaction rate constant was multiplied by several factors, which account for the limitation in process rate, namely temperature, oxygen concentration, moisture content and free air space, as will be shown in detail in section 2.2.

2.1.6 Modelling

Modelling is a powerful research and engineering tool. Its objectives are the development of a mathematical model to allow an integration of knowledge on the considered phenomena, to orientate experimental design, to reveal relationships between variables, to predict the evolution of a system and, finally, to design optimal process and management strategies (Petric & Selimbasic, 2008). The use of modelling with the aim of optimizing the design and operation of full-scale plants has been often used in composting (Haug, 1980, 1993; Cathcart *et al.*, 1986; Hansen *et al.*, 1993; Keener *et al.*, 1993, 1995, 1997, 2002, 2003, 2005; Tollner *et al.*, 1998; Das & Keener, 1996, 1997; Das *et al.*, 1998; Nielsen & Berthelsen, 2002; Scholwin & Bidlingmaier, 2003). In this context, kinetics assumes a central role, as usually it is desirable that process rate is as fast as possible.

Composting kinetics modelling has been classified as inductive or deductive by Hamelers (2001, 2004). The deductive strategy relies heavily on the theory to derive the model, but relies also on experimental data. That is, deductive modelling exploits the information of both the theory and experimental measurements. In contrast, inductive modelling relies heavily on experimental data. In this approach, also called black box modelling, a relationship between output and input is searched for. In the composting research, inductive modelling is the most common approach, and was the one adopted in this work. It is based on a set of equations that describe the dependence of composting rate on environmental factors, over a range of practical interest. In this work, the factors considered were temperature, oxygen concentration, moisture content and free air space.

2.2 The model

The simulation model developed by Haug (1993) is one of the most outstanding works in this area, and the model adopted here ended up to get many parts from it. Some changes were, however, introduced to Haug's model in some components, namely on the temperature and the oxygen correction factors, because new data and evidence was produced since then.

In the end, the basic model equation and the correction factors were chosen from the literature, taking into account:

- Strength of experimental support;
- Acceptance (adoption) by researchers in the area.

The several components of the model are discussed in detail in the following sections.

2.2.1 First-order kinetics

Review of the literature showed that the first-order kinetics is the most common form of description of the composting process (table 2.1). Monod or Monod-type models have also been adopted to a significant, but smaller, extent, and these are actually more difficult to work with because they require microbial growth parameters and an estimate of the initial microbial mass. Moreover, Mason (2006) reviewed and analyzed extensively the composting models available in the literature up to the end of 2003, and concluded that the first-order models are more successful in predicting temperature profiles than Monod–type expressions. Other models, like the Gompertz equation, have also been used, but in a smaller extent. In addition, first-order kinetics has worked well in describing numerous processes involving biological oxidation (Haug, 1993). Therefore, a first-order equation was adopted in this work to model the composting process.

The composting reaction rate "r" is described here by the VS degradation rate, through the following first-order kinetic equation (Haug, 1993).

$$r = \frac{d(VS\ consumed)}{dt} = k' \times [BVS_t] \tag{2.6}$$

where (VS consumed) is the amount of VS consumed (%, in relation to the total VS content); k' is the apparent first-order reaction rate constant (d^{-1}); [BVS_t] is the amount of biodegradable VS available at time t (%, in relation to the total VS content).

As VS content is the sum of the BVS (biodegradable volatile solids) plus NBVS (non-biodegradable volatile solids) contents, the maximum amount of VS that can be consumed is equal to the total amount of BVS in the initial substrate, i.e., [BVS_o]. Therefore:

Table 2.1. List of studies found in the literature which used first-order, Monod type, Gompertz type or other equations to describe the kinetics of the composting process. The last line in the table refers to the total number of studies referred in each column.

First-order	Monod or Monod Type (including Contois)	Gompertz type	Others
Haug, 1993	Whang & Meenaghan, 1980	Silveira, 1999	Paredes *et al.*, 2002 (zero-order)
Keener *et al.*, 1993, 1995, 1997, 2003, 2005	Kaiser, 1996	Chang *et al.*, 2005, 2006a	Briski *et al.*, 2007 (n-th order)
Van Lier *et al.*, 1994	Stombaugh & Nokes, 1996	Mason, 2008a, 2008b	Gomes & Pereira, 2008 (pseudo-first-order)
Das & Keener, 1996, 1997	Agamuthu *et al.*, 2000		Petric & Selimbasic, 2008 (2.89 order)
Adani *et al.*, 1997, 2001	Huang *et al.*, 2000		
Bertoni *et al.*, 1997	Seki, 2000		
Hamoda *et al.*, 1998	de Guardia *et al.*, 2001		
Mohee *et al.*, 1998	Hamelers, 2004		
Tollner *et al.*, 1998	Zavala *et al.*, 2004a, 2004b		
Koenig & Bari, 1999	Tremier *et al.*, 2005		
Robinzon *et al.*, 1999	Xi *et al.*, 2005, 2008		
Shin *et al.*, 1999	Yamada & Kawase, 2006		
Bari & Koenig, 2000	Qin *et al.*, 2007		
Bari *et al.*, 2000	Sole-Mauri *et al.*, 2007		
Eklind & Kirchmann, 2000	Bongochgetsakul & Ishida, 2008		
Kim *et al.*, 2000	Bueno *et al.*, 2008		
Lasaridi *et al.*, 2000	Lin *et al.*, 2008a, 2008b		
Ndegwa *et al.*, 2000			
Paredes *et al.*, 2000, 2001, 2002			
Beck-Friis *et al.*, 2001			
Higgins & Walker, 2001			
Ekinci *et al.*, 2002, 2004, 2006			
Li *et al.*, 2002			
Nakasaki & Ohtaki, 2002			
Cronjé *et al.*, 2004			
Komilis, 2006			
Ramirez-Perez *et al.*, 2007			
de Guardia *et al.*, 2008			
Mason, 2008a, 2008b, 2009			
Tosun *et al.*, 2008			
Yu *et al.*, 2009			
43	20	5	4

$$r = \frac{d(VS\ consumed)}{dt} = k' \times ([BVS_o] - VS\ consumed_t) \tag{2.7}$$

Integrating equation 2.7 from time t_0 to time t, one gets:

$$VS\ consumed_t = (VS\ consumed_{t_o} - [BVS_o]) \times e^{-k' \times (t - t_o)} + [BVS_o] \tag{2.8}$$

Considering that VS degradation equals zero when t_o is also zero, equation 2.8 then becomes:

$$VS\ consumed_t = [BVS_o] \times (1 - e^{-k' \times t}) \tag{2.9}$$

k' is the uncorrected first-order reaction rate constant, and is a measure of the overall efficiency of each composting process in analysis. This corresponds to the first-order reaction rate constants normally presented in the bibliography. k' is the product of k (corrected first-order rate constant) by the environmental conditions factors (Haug, 1993):

$$k' = k \times F(T) \times F(MC) \times F(O_2) \times F(FAS) \quad (2.10)$$

where F(T), F(MC), $F(O_2)$ and F(FAS) are the correction factors for temperature (T), moisture content (MC), oxygen concentration in the free air space ($[O_2]$) and free air space (FAS), respectively.

The sum of all the limitations taken in consideration is represented by F(TOT), and is defined as the product of the four correction factors:

$$F(TOT) = F(T) \times F(MC) \times F(O_2) \times F(FAS) \quad (2.11)$$

$$k' = k \times F(TOT) \quad (2.12)$$

$$VS\ consumed_t = [BVS_o] \times (1 - e^{-k \times F(T) \times F(MC) \times F(O_2) \times F(FAS) \times t}) \quad (2.13)$$

Equation 2.13 will be used for the determination of k, the corrected first-order rate constant.
The definition of the environmental correction factors will be made in the following sections.

2.2.2 Correction factor for temperature – F(T)

There is an extensive set of equations in the literature to describe the dependence of the composting rate on T (table 2.2).

Haug's (1993) equation for temperature correction (table 2.2) was taken from Andrews & Kambhu (1973) (cited in Haug (1993)), and calibrated with the data from Schulze (1962) and Wiley & Pearce (1957) (cited in Haug (1993)) on composting of waste materials similar to the ones studied in this work. Haug's (1993) equation was adopted by a number of researchers (Bertoni et al 1997; Tollner *et al.*, 1998; Robinzon *et al.*, 1999; Kim *et al.*, 2000; Ndegwa *et al.*, 2000; Li *et al.*, 2002; Cronjé *et al.*, 2004; Briski *et al.*, 2007; Petric & Selimbasic, 2008). However, this equation was not chosen here for two main reasons:

Table 2.2. List of functions found in the literature to describe the composting rate dependence on T. All non-described parameters are empirical. (To be continued)

Reference	Model equations	Parameters definition	Model origin / use
Schulze, 1962	$y = 0.1 \times 10^{0.028 \times T}$	y - oxygen consumption rate (mg O_2 / g volatile matter / hour) T - temperature (ºC)	Developed from garbage and sewage sludge composting data.
Jeris & Regan, 1973a	$Y=aT^2+bT+c$	Y - composting rate (mg O_2 or CO_2 /d / g volatile matter) T - temperature (ºC)	Developed from mixed refuse composting data.
Cathcart *et al.*, 1986	$Y=a+bT+cH+dT^2+eH^2$	Y - composting rate (kg CO_2 generated/kg initial dry matter) H - moisture content (%, wet basis); T - temperature(ºC)	Developed from crab scrap + straw composting data.
Haug, 1993	$k_T = k_{20} \times \left[1.066^{(T-20)} - 1.21^{(T-60)}\right]$	k_T - 1st order reaction rate constant at temperature T (d^{-1}) k_{20} - 1st order reaction rate constant at 20ºC (d^{-1}) T - temperature (ºC)	Developed from mixed compostables composting data, to integrate a composting model.
Kaiser, 1996	f(T)=Tx(80-T)/1600, for microorganisms that grow from 0ºC up to 80ºC; f(T)=Tx(60-T)/[20.(80-T)], for microorganisms that grow from 0ºC up to 60ºC.	f(T) - T coefficient T - temperature (ºC)	Developed to describe the T dependent growth of single microbial species. Equation is part of a composting model developed by the author.
Lasaridi *et al.*, 1996	$\sqrt{(SOUR)} = b(T - T_{\min})[1 - e^{c(T-T_{\max})}]$	SOUR - specific oxygen uptake rate (mg O_2 / g VS / hr) T_{min} and T_{max} - as defined in this work (K) T - temperature (K)	Fitting of the model of Ratkowsky *et al.* (1983) to olive mill wastewater and extracted olive press-cake composting data.
Stombaugh & Nokes, 1996	$k_T = T/(T2-T1)$ T1<T≤T2 $k_T = 1.0$ T2<T≤T3 $k_T = 3.75-[(T/(T2-10)]$ T3<T	k_T - temperature coefficient T - temperature (ºC)	Equation is part of a composting model applied on trials with cracked corn and pelleted corn cobs.

Table 2.2. List of functions found in the literature to describe the composting rate dependence on T. All non-described parameters are empirical. (Continuation)

Reference	Model equations	Parameters definition	Model origin / use
Mohee *et al.*, 1998	$k=-8x10^{-6}T^3+0.008T^2-0.0238T+0.2643$	k - first-order reaction rate constant (d^{-1}) T - temperature (ºC)	Developed from sugarcane bagasse composting data. Equation is part of a composting model used by the authors.
Koenig & Bari, 1999; Bari & Koenig, 2000; Bari *et al.*, 2000	$k_T = A \times e^{-\frac{Ea}{R}(\frac{1}{T})}$	Ea - activation energy (kJ/mol) R - ideal gas constant (kJ/mol.K) T - absolute temperature (K) A - frequency factor	Arrhenius equation applied to composting trials with food waste, paper, sawdust.
Richard & Walker, 1999, 2006	i) $R_{CO_2} = k \times \left[\theta_1^{(T-T_{r1})} - \theta_2^{(T-T_{r2})} \right]$ ii) $R_{CO_2} = b \times (T - T_{\min}) \times (1 - e^{\left[c \times (T - T_{\max})\right]})$ iii) $R_{CO_2} = \frac{R_{CO_2 opt}(T - T_{\max})(T - T_{\min})^2}{(T_{opt} - T_{\min})\left[(T_{opt} - T_{\min})(T - T_{opt}) - (T_{opt} - T_{\max})(T_{opt} + T_{\min} - 2T)\right]}$	Parameters as defined in the text for equations 2.14, 2.15 and 2.16	Models of (i) Andrews & Kambhu (1973) (cited in Richard & Walker (2006)) / Haug (1993), (ii) Ratkowsky *et al.* (1983) and (iii) Rosso *et al.* (1993) applied to composting trials with: (i) Dry dog food and maple wood chips; (ii) sewage sludge and maple wood chips. Aim was the study of the composting rate dependence on T.
de Guardia *et al.*, 2001	T(80-T)/1600	T - temperature (ºC)	Origin not mentioned. Equation is part of a simulation model developed by the authors.
Ekinci *et al.*, 2001, cited in Ekinci *et al.*, 2006 ; Ekinci *et al.*, 2004, 2006; Keener *et al.*, 2003, 2005	$X_T = e^{-0.5[(T-a)/b)^2]}$	X_T - temperature correction factor for the first-order reaction rate constant (fractional) T - temperature (ºC)	Developed from experimental data on composting trials with paper mill sludge and broiler litter. Equation is part of a simulation model used by the authors.

Table 2.2. List of functions found in the literature to describe the composting rate dependence on T. All non-described parameters are empirical. (Continuation)

Reference	Model equations	Parameters definition	Model origin / use
Nielsen & Berthelsen, 2002	$k = A \times e^{(a(T-T_o))} \times \frac{1}{e^{(b(T-T_1))}+1}$	k - rate of decomposition To - an arbitrary temperature constant T_1 - inflexion point temperature	Developed on a theoretical basis.
Nelson *et al.*, 2003	$k(T) = \frac{A_1 \times e^{-\frac{E_1}{RT}}}{1 + A_2 \times e^{-\frac{E_2}{RT}}}$	E_1 - activation energy for biomass growth (J $mol^{-1)}$ E_2 - activation energy for inhibition of biomass growth (J $mol^{-1)}$ A_1 - pre-exponential factor for biomass growth (s^{-1}) A_2 - pre-exponential factor for the inhibition of biomass growth (s^{-1}) R - ideal gas constant (J K^{-1} mol^{-1})	Developed on a theoretical basis.
Hamelers, 2004	$p(T) = p(T_r) \times e^{-\frac{E}{R}(\frac{1}{T}-\frac{1}{T_r})}$	T_r - reference T (K) P(T) - parameter value p at the reference T E - activation energy (kJ mol^{-1}) R - gas constant (kJ mol^{-1} K^{-1})	Developed on a theoretical basis.
Kulcu & Yaldiz, 2004	$k_T = \frac{\frac{a}{Mc}}{T - C \times b} \times e^{(T \times c - d \times \frac{Mc}{T})}$	k_T - rate of decomposition (g VS/g VS day) T - temperature (ºC) Mc - Moisture content (%,wet basis) C - CO_2 production rate (%)	Developed from grass trimmings, tomato, pepper and eggplant composting data.
Zavala *et al.*, 2004a	$\mu_{HT} = 6 \times 1.07^{(T-20)}$	μ_{HT} - maximum growth rate of biomass at temperature T (d^{-1}) T - temperature (ºC)	Arrhenius equation applied to composting trials of faeces and sawdust.

Table 2.2. List of functions found in the literature to describe the composting rate dependence on T. All non-described parameters are empirical. (Continuation)

Reference	Model equations		Parameters definition	Model origin / use
Xi *et al.*, 2005, 2008 Qin *et al.*, 2007	$k_T = e^{-\frac{E_A}{R}\times(\frac{1}{T+273}-\frac{1}{T_S+273})}$ $k_T = \frac{T_L - T}{T_L - T_M}$ $k_T = 0$	$T \le T_M$ $T_M \le T \le T_L$ $T \ge T_L$	T - temperature (ºC) T_s - preference T (ºC) T_M - threshold T (ºC) T_L - maximum allowable T for microbial activities (ºC) k_T - correction function for T E_A - activation energy (J/mol) R - universal gas constant (J/mol.K)	A Chinese reference is cited by the authors for these equations, which describe microbial specific growth rate dependence on T. Equation is part of a composting model applied on experimental trials with domestic solid wastes.
Bongochgetsakul & Ishida, 2008	$\mu_T(T) = \frac{A_T \times e^{-\frac{E_1}{RT}}}{1 + K_T \times e^{-\frac{E_2}{RT}}}$		$\mu_T(T)$ - T dependent maximum specific growth rate (s^{-1}) T - temperature (K) Other parameters not defined by the authors	Modification of the Arrhenius equation by Mayo (1997) (cited in Bongochgetsakul & Ishida (2008)). Equation is part of a model applied on a theoretical exercise.
Petric & Selimbasic, 2008	$k_T = a \times \left[b^{(T-20)} - c^{(T-60)} \right]$		k_T - correction function for T (fractional) T - temperature (ºC)	Modification of the equation proposed by Haug (1993). Equation is part of a model applied to poultry manure + straw composting trials.
Yu *et al.*, 2009	For mesophilic bacteria: k_{temp}= 0.033xT k_{temp}= 1.0 k_{temp}= -0.067xT+3.667 For thermophilic bacteria: k_{temp}= 0.1xT-4.0 k_{temp}= 1.0 k_{temp}= -0.067xT+3.667	 0≤T≤30 30≤T≤40 40≤T≤55 40≤T≤50 50≤T≤55 55≤T≤75	k_{temp}- T correction factor for the first-order reaction rate constant T - temperature (ºC)	Equations proposed by the authors. These are part of a composting model applied on experimental trials with dairy manure and straw.

i) Schulze (1962) obtained his process temperature data by measuring reactor exhaust temperature; however, rotating-drum exhaust temperatures can be close to the maximum substrate temperature and significantly higher than the mean substrate temperature, as observed by Richard (1997) in a pilot-scale reactor system. Therefore, the calibrated function for the reaction rate *versus* temperature may have a significant bias.

ii) Schulze data indicates an increase in reaction rate with temperature up to 70ºC, the highest temperature in his study. For the same reason as in (i), the reaction rate temperature optimum is very likely to be overestimated.

Therefore, another equation was chosen to describe the effects of temperature on the reaction rate constant. Of those listed in table 2.2, the one that seems to have a stronger experimental support and wider acceptance by the composting research community is the one presented by Richard (1997) and Richard & Walker (1999, 2006). This equation is based in the model of Rosso *et al.* (1993) and on the experimental and simulation work done by Richard (1997) on the application of this model to the composting process. Rosso *et al.* (1993) developed this equation for the description of the growth rate of individual microorganisms as a function of temperature. Richard (1997) performed pilot and laboratory composting assays where reaction rates where measured at different T (35 ºC, 45 ºC, 55 ºC and 65ºC), [O_2] (1%, 4% and 21% O_2 (v/v)) and MC (36% - 60%) conditions, for two different composting mixtures: dry dog food with maple wood chips as a bulking agent and 10% of compost as inoculum; and anaerobically digested, polymer-dewatered sewage sludge, also with maple wood chips as a bulking agent, but with no inoculum added. The extensive set of experimental data produced gives a good support to the variation of reaction rate with T. Finally, the effect of temperature on the reaction rate constant was modelled by Richard (1997) and Richard & Walker (1999, 2006) using three mathematic equations:

i) Andrews & Kambhu (1973) (cited in Richard & Walker (2006)) / Haug (1993):

$$R_{CO_2} = k\left[\theta_1^{(T-T_{r1})} - \theta_2^{(T-T_{r2})}\right] \tag{2.14}$$

where

R_{CO2} - CO_2 evolution rate (g CO_2/(kg VS)/day)

T - temperature (ºC)

k - parameter defined as the first-order rate constant for the reference temperature T_{r1} (day^{-1})

T_{r1}, T_{r2} - reference T parameters (°C)

θ_1, θ_2 - empirically estimated coefficients

ii) Ratkowsky et al. (1983)

$$R_{CO_2} = b(T - T_{\min})(1 - e^{\left[c\left(T - T_{\max}\right)\right]}) \quad (2.15)$$

where

R_{CO2} - CO_2 evolution rate (g CO_2/(kg VS)/day)

T - temperature (ºC)

T_{max} - maximum temperature for biodegradation (ºC)

T_{min} - minimum temperature for biodegradation (ºC)

(at T_{max} and T_{min}, the biodegradation rate is zero)

b - empirically estimated coefficient which determines the maximum rate of biodegradation

c - empirically estimated coefficient which determines the behaviour of the model near the optimum temperature

iii) Rosso et al. (1993)

$$\mathrm{R}_{\mathrm{CO}_2} = \frac{R_{CO_2 opt}(T - T_{\max})(T - T_{\min})^2}{(T_{opt} - T_{\min})\left[(T_{opt} - T_{\min})(T - T_{opt}) - (T_{opt} - T_{\max})(T_{opt} + T_{\min} - 2T)\right]} \quad (2.16)$$

where

R_{CO2} - CO_2 evolution rate (g CO_2/(kg VS)/day)

R_{CO2opt} - CO_2 evolution rate at the optimum temperature (g CO_2/(kg VS)/day)

T - temperature (ºC)

T_{min} - minimum temperature for biodegradation (ºC)

T_{opt} - optimum temperature for biodegradation (ºC)

T_{max} - maximum temperature for biodegradation (ºC)

All the three equations above are similar in shape and proved capable of modelling a wide range of experimental data, but the equation of Rosso *et al.* (1993) was the one that performed better. This model is also very "user friendly", as its parameters have a clear biological significance, and can each be measured in the laboratory. A final benefit is the immediate usefulness of the parameters in engineering design and process control (Richard, 1997; Richard & Walker, 1999, 2006).

A list of authors adopting this model for their composting simulation studies is indicated in table 2.3.

Table 2.3. List of authors that adopted the model of Rosso *et al.* (1993) to simulate the T effect on composting rate, and corresponding parameters used.

Reference	Material	T_{min} (ºC)	T_{opt} (ºC)	T_{max} (ºC)
Richard, 1997; Richard & Walker 1999, 2006	Solid food waste	5	58.6	71.6
Richard, 1997; Richard & Walker 1999, 2006	Sewage sludge	5	59.7	70.5
Higgins & Walker, 2001	Solid food waste	5	58.6	71.6
Tremier *et al.*, 2005	Sewage sludge from food industry + pine barks	0	38.5	63.0 – 67.8
Sole-Mauri *et al.*, 2007	Mixtures of fruit pulp, paper pulp, cattle manure, municipal sewage sludge, agro-industrial sewage sludge, poultry manure and poultry egg wastes	5.2* or 30.8**	35.4* or 57.2**	44* or 65.5**
Mason, 2008b***	-	5	59	71
Mason, 2009	Waste recipe (7.1% ostrich feedstuff + 8.9% paper + 0.9% compost + 26.7% woodchips + 55.5% Water)	5 5 5	59 55 50	85 80 80
In this work		5	58.6	71.6

*For mesophilic microorganisms.
**For thermophilic microorganisms.
*** Mason (2008b) used this temperature dependence model in the temperature correction of substrate degradation profiles, for the purpose of evaluating substrate degradation patterns from the data of several authors.

The following equation will thus be used here to describe the correction factor for T, F(T):

$$F(T) = \frac{(T - T_{max})(T - T_{min})^2}{(T_{opt} - T_{min})\left[(T_{opt} - T_{min})(T - T_{opt}) - (T_{opt} - T_{max})(T_{opt} + T_{min} - 2T)\right]} \quad (2.17)$$

where parameters definition is as indicated for equation 2.16.

The values chosen for T_{min}, T_{opt} and T_{max} in equation 2.17 were the ones estimated by Richard (1997) and Richard & Walker (1999, 2006) for dog food composting with maple wood chips; according to VanderGhenst *et al.* (1997), dog food is quite similar to food waste, namely because their fat, fibre and protein contents are similar. By doing so, the curve shape obtained by these authors for the dependence of the reaction rate on temperature is respected, which is a "comfortable" option as this curve shape and parameters are based on a strong set of experimental data. Nevertheless, some considerations will be made about each of these parameters.

Minimum temperature (T_{min}): 5ºC

This was the value set for describing the dependence of the composting rate on temperature, using the model of Rosso *et al.* (1993), by several authors (table 2.3).

This value is also in the range of temperatures used for storing food in refrigerators, where microbial activity is kept to a minimum. Besides, by setting T_{min} to 5ºC, this does not mean k will have a fast increase when the temperature rises; in fact, k is very close to zero until about 10ºC, and then starts to increase slowly (figure 2.2).

Nevertheless, composting experiments carried out at 5ºC were not found in the literature. Therefore, other values of T_{min} will be tested in the simulation analysis (section 5.2.2), namely 0ºC, 10ºC and 20ºC.

Optimum temperature (T_{opt}): 58.6ºC

This was the value determined experimentally and with data fitting to the model of Rosso *et al.* (1993) by Richard (1997) and Richard & Walker (1999, 2006) for composting dry dog food with maple wood chips. The value obtained by these authors for anaerobically digested, polymer-dewatered sewage sludge with maple wood chips was 59.7ºC, quite close to the one adopted (58.6ºC). Nevertheless, the value 58.6ºC was used because, as mentioned above, it was assumed that dog food is more similar to the organic fraction of MSW than sewage sludge (VanderGheynst *et al.*, 1997).

Other researchers used this value, or one very close to it (table 2.3), namely Higgins & Walker (2001) and Mason (2008b, 2009).

This value is also within the range of the reported optimum temperature values for the type of material studied in the present work (table 2.4). The average of the values presented in the table is 59.2ºC, without considering the values from Hamoda *et al.* (1998) and Eklind *et al.* (2007), because these authors only studied three process temperatures, which were very distant from each other. This average value for the optimum temperatures is very close to the value adopted here for the model.

Maximum temperature (T_{max}): 71.6ºC

The T_{max} value adopted here for the model is also the one estimated by Richard (1997) and Richard & Walker (1999, 2006) for dry dog food with maple wood chips.

Data evidence supporting this choice comes from other authors, namely:

- Suler & Finstein (1977) studied the composting of food waste mixed with paper in lab-scale reactors at temperatures in the 48-72ºC range, and measured very low composting rates at 72ºC;
- Keener *et al.* (1997) performed composting tests on several types of materials, including MSW, and observed that MSW achieved high decomposition rates up to 70ºC, but exceeding 72ºC would stop the process for all materials.

Table 2.4. Optimum temperatures for composting, collected from the literature for composting materials similar to the ones analysed in this work.

Reference	Material	Temperatures studied (ºc)	Optimum temperature (ºc)
Wiley & Pearce, 1955, cited in Nielsen & Berthelson, 2002	Kitchen waste	-	60
Gootas, 1956	Organic waste in general (focus on sludge and MSW)	-	60
Schulze, 1960	Garbage recipe	27 - 63	63
Schulze, 1962	Garbage mixed with other wastes	35 - 70	55 - 65
Jeris & Regan, 1973a	MSW	35 - 70	60
Suler & Finstein, 1977	Food waste mixed with paper	48,52,56,60,64,68,72	56 - 60
Clark *et al.*, 1977, 1978	Garbage recipe	42,45,48,51,54,57	54
Regan, 1979	Mixed refuse	35,40,44,45,50,55,63,64,65,70	64
Richard, 1997; Richard & Walker 1999, 2006	Dog food + woodchips	35,45,55,65	58,6
Hamoda *et al.*, 1998	MSW after hammer mill	20, 40, 60	40*
Huang *et al.*, 2000	Vegetable waste + rice husks	45,50,55,60,65	57,1
Eklind *et al.*, 2007	Household waste + straw	40, 55, 67	55*
Mean value			**59,2**

* Values not considered in the calculation of the mean, because big gaps existed between the T studied.

However, this T_{max} of 71,6ºC was obtained by Richard (1997) and Richard & Walker (1999, 2006) by extrapolation, as temperatures studied in his lab-scale reactors were 35, 45, 55 and 65ºC. Besides, evidence and statements were also found in the literature which may lead one to think that T_{max} can be higher, namely:

- Regan (1979) reported a reaction rate (oxygen uptake) for the composting of mixed refuse at 70ºC which is about 76% the one observed at the optimum temperature 64ºC;
- Beffa *et al.* (1996) reported isolation of high numbers of thermophilic bacteria related to the genus *Thermus* from full-scale composting systems treating kitchen waste, yard waste, sewage sludge and shredded wood, operating in the temperature range of 65-82ºC; isolates grew fast on a rich complex medium at temperatures between 40ºC and 80ºC, with optimum growth between 65ºC and 75ºC;
- Kaiser (1996) states that, in composting, growth of microorganisms occurs up to 80ºC, although only some bacteria remain active up to this temperature;
- Stombaugh & Nokes (1996) used 75ºC as T_{max} in their simulation model;

- Haug (1993) states that temperatures in compost piles can go up to 80ºC, but this value is rarely exceeded; 80ºC was used by Haug (1993) for T_{max};
- Gootas (1956) points out that a few of the thermophilic organisms are still active at temperatures above 70ºC;
- Miller *et al.* (1989) state that biological composting activity ceases at 75–82ºC;
- Mason (2009) used 80ºC and 85ºC for T_{max} to describe the dependence of the composting rate on temperature, with the model of Rosso *et al.* (1993), for composting of 7.1% ostrich feedstuff + 8.9% paper + 0.9% compost + 26.7% woodchips + 55.5% water. The value of 80ºC gave a better fit to the results, though.

Given this, other values of T_{max} will also be tested in the simulations (section 5.2.2), namely 68ºC and 80ºC.

Nevertheless, no definite values are established for T_{opt}, T_{min} and T_{max}. It is evident from the literature that a considerable effort was made in order to define T_{opt}, but this seems to vary according to the type of material. Besides, Richard (1997) and Richard & Walker (1999, 2006) obtained results showing that the optimal temperature varies along the process, and is also dependent on moisture content and oxygen content, which makes things even more complicated.

Regarding T_{min} and T_{max}, there is not so much experimental evidence as for T_{opt}; especially for T_{min}, data is very scarce. For T_{max}, there is some experimental data in the literature, which seem to indicate this parameter should be somewhere between 70ºC and 80ºC.

Further research is needed in this area for the definition of T_{opt}, T_{min} and T_{max}, and especially for the study of the dependence of these parameters on the type of material, process time, and the other environmental conditions.

The resulting correction factor for T adopted here is then presented in equation 2.18, and has the graphical form plotted in figure 2.2.

$$F(T) = \frac{(T - 71.6)(T - 5)^2}{(58.6 - 5)\left[(58.6 - 5)(T - 58.6) - (58.6 - 71.6)(58.6 + 5 - 2T)\right]} \tag{2.18}$$

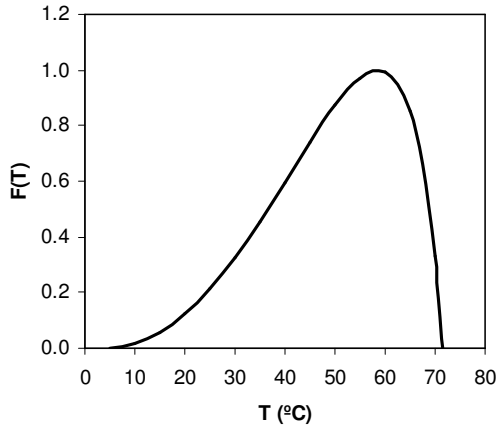

Figure 2.2. Correction factor for T, F(T) (equation 2.18), adopted in this work.

The model for F(T) and corresponding parameters adopted here are further supported by the data of Eklind *et al.* (2007), which studied the composting of household source separated waste with wheat straw in a lab-scale reactor, at three different T: 40ºC, 55ºC and 67ºC. k values where estimated according to the procedure described in sections 4.2.1 and 4.2.6, and where plotted in figure 2.3. k variation with T, according to equation 2.18, is also plotted. Experimental data agreement with the model is quite satisfactory.

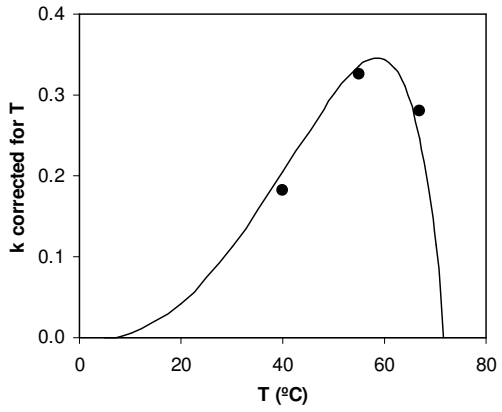

Figure 2.3. Plot of the k values estimated from the data of Eklind *et al.* (2007) at 40ºC, 55ºC and 67ºC (•) against T , and fitting (—) according to the T correction function adopted in this work.

2.2.3 Correction factor for oxygen – F(O_2)

In the case of oxygen, the correction factor proposed by Haug (1993) is the following:

$$F(O_2) = \frac{[O_2]}{[O_2] + K_{O_2}} \tag{2.19}$$

where

$[O_2]$ is the concentration of molecular oxygen in the free air space (%, in volume)

K_{O_2} is the half saturation constant (%, in volume), assumed to be 2% by Haug (1993)

The development of this model by Haug (1993) was heavily based in the work of Schulze (1962), which carried out composting trials of garbage with a number of conditioning materials, in a 208 l rotating, intermittently fed reactor. Schulze observed that oxygen concentrations of about 5% did not impose severe oxygen limitations on the reaction rate. Hence, by assuming that the effect of oxygen concentration could be modelled by a Monod-type expression, and that the K_{O_2} was 2% of oxygen (v/v), Haug (1993) ensured that oxygen effects on the reaction rate were minimal at 5 %. Also, with this equation, the rate of organic decomposition is reduced to zero if the oxygen concentration is zero, a boundary condition known to be true for aerobic metabolism.

An inherent assumption in this approach is that particle sizes are sufficiently small to avoid oxygen transport limitations, which seemed to be the case in Schulze's (1962) experimental setup, where garbage was ground in a shredder with 1.9 cm screen openings.

This same model (equation 2.19) was used by several authors, as indicated in the following table, together with the half-saturation constants used.

Table 2.5. List of authors who adopted $F(O_2)$ developed by Haug (1993) (equation 2.19) and corresponding K_{O_2} values.

Reference	Half-saturation constant, K_{O_2} (%, v/v)
Haug, 1993	2
Stombaugh & Nokes, 1996	5.3
Bertoni *et al.*, 1997	2
Tollner *et al.*, 1998	2
Kim *et al.*, 2000	2
Li *et al.*, 2002	2
Cronjé *et al.*, 2004	2
Xi *et al.*, 2005, 2008	2
Qin *et al.*, 2007	2
Bongochgetsakul & Ishida, 2008	-
Petric & Selimbasic, 2008	5.3
Yu *et al.*, 2009	-

A detailed work that analysed the reaction rate dependence on oxygen was developed by Richard (1997), Richard & Walker (1999) and Richard *et al.* (2006). This work was based on an extended set of experimental data, the same that the authors used to calibrate the temperature model (section 2.2.2). Four different models were studied by these authors for the reaction rate dependence on oxygen, namely (according to the authors' nomenclature) the one-parameter saturation model (equation 2.20), the modified one-parameter saturation model

(equation 2.21), the two-parameter saturation model (equation 2.22) and an exponential model (equation 2.23).

One-parameter saturation model

$$F(O_2) = \frac{[O_2]}{K_{O_2}(T, MC) + [O_2]} \tag{2.20}$$

where

$K_{O_2}(T, MC) = 0.79 - 0.041T + 40MC$

$[O_2]$ is the oxygen concentration (%, v/v);

K_{O_2} is the half saturation constant (% O_2, v/v);

T is the temperature (ºC);

MC is the moisture content (fractional, on a wet basis).

Modified one-parameter saturation model

$$F(O_2) = \frac{[O_2]}{F_{O_2}(21\%) \times (K_{O_2}(T, MC) + [O_2])} \tag{2.21}$$

where

$$F_{O_2}(21\%) = \frac{20.9}{K_{O_2}(T, MC) + 20.9}$$

$K_{O_2}(T, MC) = 1.504 - 0.060T + 48MC$

$[O_2]$ is the oxygen concentration (%, v/v);

K_{O_2} is the half saturation constant (% O_2, v/v);

T is the temperature (ºC);

MC is the moisture content (fractional, on a wet basis).

Two-parameter saturation model

$$F(O_2) = \frac{\xi[O_2]}{K_{O_2} + [O_2]} \tag{2.22}$$

where

$[O_2]$ is the oxygen concentration (%, v/v);

K_{O_2} is the half saturation constant (% O_2, v/v);

ξ is the value of $F(O_2)$ when $O_2 >> K_{O_2}$.

Exponential model

$$F(O_2) = 1 - e^{(-K_{O2} \times [O_2])} \quad (2.23)$$

where

$[O_2]$ is the oxygen concentration (%, v/v);

K_{O_2} is the negative exponent parameter ($[\%\, O_2$, v/v$]^{-1}$).

For the full range of experimental data, the one-parameter models, both the simple (equation 2.20) and the modified version (equation 2.21) performed better than the two-parameter saturation model (equation 2.22) and the exponential model (equation 2.23). Moreover, it was concluded that the modified one-parameter saturation model would be particularly suitable for the description of high oxygen operating composting systems, while the simple one-parameter model should be used for systems operating at lower oxygen levels. However, neither of the models where applicable for oxygen concentrations below 2% (v/v), due to the lack of data at the extreme lower end of the curve and the selection of a mathematical form for the model that is clearly unrealistic at very low oxygen concentrations (Richard, 1997; Richard & Walker, 1999; Richard *et al.*, 2006).

In the present work, it was common to have oxygen measurements in the range of 0-2 %, which was a serious obstacle to the adoption of these models.

Moreover, a rather unexpected behaviour was observed by the authors (Richard, 1997; Richard & Walker, 1999; Richard *et al.*, 2006). At low moisture and high temperature conditions, reaction rates increased with decreasing oxygen concentrations (measured through CO_2 emissions). Extrapolating the models to higher temperature and lower moisture values, out of the ranges studied by these authors, but observed in the present work, this effect is even more marked. This was another barrier to the adoption of these models. In fact, to our knowledge, there is no other report in the literature where this behaviour was observed, and this demands for further research, as suggested by the authors. It was also suggested that this effect could be caused by the action of facultative and anaerobic microorganisms, which would mean that substrate degradation rates for anaerobic processes would exceed those of aerobic processes, under these conditions (high temperature, low moisture) (Richard *et al.*, 2006). An alternative hypothesis is the increased significance of chemical oxidation of substrates, which, according to Haug (1997), is favoured at these conditions of high temperature and low moisture.

Nevertheless, even without fully adopting the models presented above for the reaction rate dependence on oxygen (Richard, 1997; Richard & Walker, 1999; Richard *et al.*, 2006), and

given that these models have a strong experimental support, some important information was taken, namely:

- The use of a Monod-type expression, either in the form of the simple or of the modified one parameter saturation model, is consolidated;
- The K_{O_2} of 2 %, used by Haug (1993) and other authors (see table 2.5), is probably too high;
- An estimate for K_{O_2} was obtained from these authors data (Richard, 1997; Richard & Walker, 1999; Richard *et al.*, 2006). In the absence of a more precise criterion, we estimated K_{O_2} by calculating a mean value for this constant over the temperature and moisture conditions studied, which are not much narrower than the conditions observed in the plants studied in the present work. This was done by varying the temperature and moisture conditions along constant relative intervals, and by determining the mean of K_{O_2} along these set of conditions. T was varied from 35ºC up to 64.9ºC with 16.7% relative increments, while MC varied from 36% to 59.3% with 13.3% relative increments. K_{O_2} was calculated for all T and MC values combinations using the $K_{O_2}(T,MC)$ function of equation 2.21. In the end, a mean K_{O_2} value of 0.83 % was obtained, which was used in the present work;
- The modified one-parameter model proposed seems to be more realistic than the simple version of the model, especially at high oxygen concentrations. In fact, the modified version allows the correction factor to equal 1, when oxygen concentration reaches its normal value in the atmosphere, i.e., 20.95 % (v/v), whereas the simple model equals 0.96, for the same oxygen concentration, when a K_{O_2} of 0.83 % is used.

Thus, the modified version of the one-parameter saturation model will be used here (equation 2.24, figure 2.4).

$$F(O_2) = \frac{[O_2]}{F_{O_2}(20.95\%) \times (0.83 + [O_2])} \tag{2.24}$$

where

$$F_{O_2}(20.95\%) = \frac{20.95}{0.83 + 20.95}$$

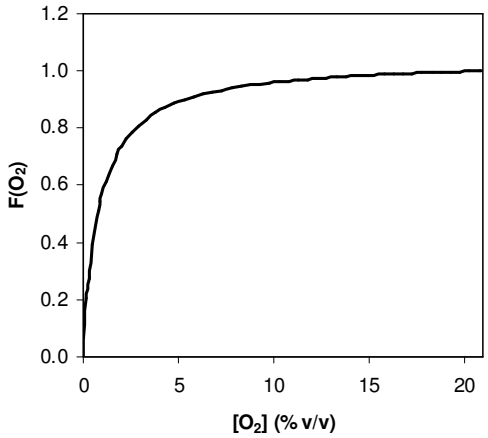

Figure 2.4. Correction factor for $[O_2]$, $F(O_2)$ (equation 2.24), adopted in this work.

Another interesting set of data comes from Beck-Friis *et al.* (2003), which composted household source separated food waste with wheat straw in a lab-scale reactor at three different oxygen levels, namely 1 %, 2.5 % and 16 % of $[O_2]$ (v/v). Reaction rate constants at those three different oxygen levels were evaluated by the cumulative carbon-CO_2 emission profiles by digitising the information (4.2.6) for each oxygen level and fitting to a one-time scale exponential model (4.2.1). The reaction rate constants estimated for the three oxygen levels were then used to estimate the K_{O_2} by fitting to equation 2.21 (figure 2.5); a K_{O_2} value of 0.72 % was obtained with this data, which compares well to the value estimated from the data of Richard (1997), Richard & Walker (1999) and Richard *et al.* (2006), i.e., 0.83 %.

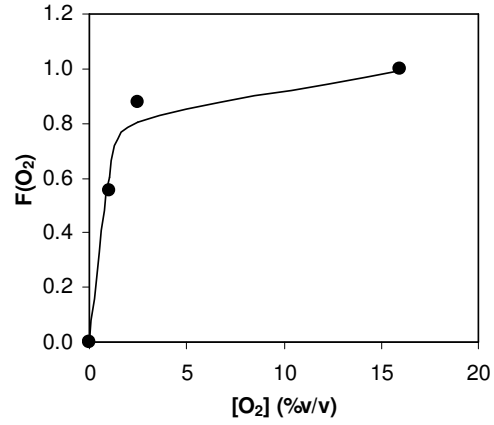

Figure 2.5. $F(O_2)$ values (•) estimated from the experimental data of Beck-Friis *et al.* (2003) at 1 %, 2.5 % and 16 % of $[O_2]$ (v/v) and fitted curve (—) for $F(O_2)$, according to the correction function adopted in this work (equation 2.21).

Another work was found in the literature (Michel & Reddy, 1998) which presents data that can be used to estimate the variation of composting rate with oxygen concentration. However, a different type of material was composted- yard trimmings - and so this information was not used.

2.2.4 Correction factor for moisture content – F(MC)

Modelling the effect of MC (moisture content) on the composting reaction rate was carried out using the correction factor developed by Haug (1993) (equation 2.25, figure 2.6).

$$F(MC) = \frac{1}{e^{(-17.684(1-[DM])+7.0622)}+1} \tag{2.25}$$

where

[DM] is the fractional dry matter content of the composting material, which equals (1-MC).

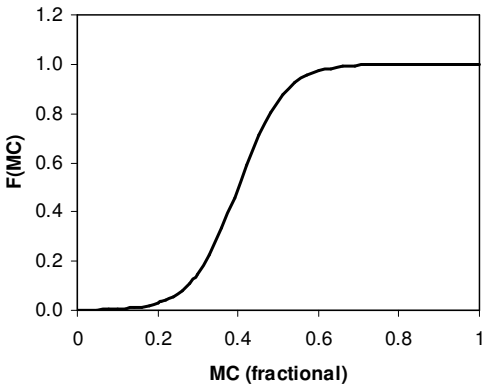

Figure 2.6. Correction factor for MC, F(MC) (equation 2.25), adopted in this work.

Haug (1993) based this model on several sets of data: Schulze (1961) with simulated food waste rewetted compost; Jeris & Regan (1973b) for a municipal solid waste with a high paper content; and Snell (1957) (cited in Haug (1993)) for ground garbage, on the variation of the composting rate with moisture content. According to these data sets, composting rate increases with increasing moisture up to a level, above which it starts to decrease. This decrease in activity is not due to any direct effect of moisture itself on the microbial community, but to the decrease in FAS caused by the increasing moisture levels. At sufficiently high moisture contents, FAS can go down to levels where oxygen storage and transport through the void spaces is reduced, thereby causing an oxygen limitation in the process. As such, F(MC) will account solely for the effect of moisture, and the rate reduction at high MC levels will be accounted for by the free air space correction factor, F(FAS) (section 2.2.5).

Several other authors adopted this correction factor in their work, namely Bertoni *et al.* (1997), Tollner *et al.* (1998), Kim *et al.* (2000), Ndegwa *et al.* (2000), Higgins & Walker (2001), Li *et al.* (2002), Cronjé *et al.* (2004) and Petric & Selimbasic (2008).

According to the F(MC) variation (figure 2.6), composting reaction rate is very slow until around 20-25% MC, it then increases up to half the maximum rate at around 40% MC, and keeps on rising until around 60% MC, where maximum speed is attained. These observations are in general agreement with data collected from the bibliography, for similar materials to those used here (tables 2.6 and 2.7).

Table 2.6. Observations / statements about the minimum moisture content levels for composting, collected from the bibliography.

Reference	Material	Experimental observation / statement
Snell, 1957, cited in Gray *et al.*, 1971b	Ground refuse	The rate of composting fresh material at MC in the range 20-25% is less than 15% of the rate at optimum MC levels
Spohn, 1968, cited in Gray *et al.*, 1971a	Ground refuse	Idem Snell (1957) (cited in Gray *et al.* (1971b)); additionally, Spohn still detected some activity at 5% MC
Gray *et al.*, 1971b	Solid waste in general	Biological activity is greatly reduced at substrate moisture contents below 30%

Other models for the effect of MC on composting rate were found in the literature (table 2.8). Nonetheless, Haug's (1993) model was chosen over these, since none has been as widely used, and because Haug's has a satisfactory experimental support.

A final note goes to results that show that optimum moisture content varies along the composting process; factors like particle size and material structure, which vary along the process, cause MC_{opt} also to vary (Hamelers & Richard, 2001; Richard *et al.*, 2002). The F(MC) correction factor adopted here and all the models in table 2.8 but one (Hamelers & Richard, 2001; Richard *et al.*, 2002) assume that the rate dependence on MC is constant along process time.

The waste material studied here (pre-treated MSW) is associated with one further complication, which is caused by the high inert materials content in the composting waste (Morvan *et al.*, 2002, 2003). Materials like glass, plastic and stones do not absorb water, and therefore cause the apparent MC determined to be lower than the real MC of the biodegradable materials. A correction should ideally be made in order to work with the true MC in the biodegradable materials, which may be achieved either if all the inert materials are removed before MC determination or if their content is also determined.

Table 2.7. Optimum moisture content values for composting, collected from the literature for composting materials similar to the ones analysed in this work.

Reference	Material	Optimum moisture content (%)
Wiley & Pearce, 1955, cited in Jeris & Regan, 1973a	Municipal refuse (53% paper)	60 - 65
Anonymous, 1955, cited in Schulze, 1961	Garbage and other solid wastes	52 - 58
Gootas, 1956	Solid waste in general	40 - 60
Snell, 1957, cited in Gray *et al.*,1971b	Ground refuse	52 - 58
Wiley, 1957, cited in Jeris & Regan, 1973a	Refuse recipe (11-14%paper)	50 - 60
Wiley, 1957, cited in Haug, 1993	Municipal refuse (some paper removed)	60 - 65
Wiley, 1957, cited in Haug, 1993	Wrapped municipal refuse	57 - 58
Wiley, 1957, cited in Haug, 1993	Refuse with 25% soil	50 - 55
Kaibuchi, 1959, cited in Schulze, 1991	Garbage and refuse mixtures	< 60
Schulze, 1960; cited in Jeris & Regan, 1973a	Municipal refuse (33% paper)	57 - 58
Schulze, 1961	Compost from a garbage recipe	60
Schulze, 1961, cited in Jeris & Regan, 1973a	Garbage	60
Karbuchi, 1962, cited in Jeris & Regan, 1973a	Refuse and 40% night soil	50 - 55
Kneiss, 1962, cited in Jeris & Regan, 1973a	Refuse & sludge	50 - 60
Schulze, 1965, cited in Jeris & Regan, 1973a	Municipal refuse (50% paper)	47 - 60
Prescott, 1967, cited in Jeris & Regan, 1973a	Municipal refuse and sludge (some paper removed)	60 - 70
Jeris *et al.*, 1968, cited in Jeris & Regan, 1973b	Refuse recipe (100% paper)	65
Spohn, 1968, cited in Gray *et al.*, 1971a	Ground refuse	50
Jeris & Regan, 1973b	Refuse (60-70% paper)	67
Suler & Finstein, 1977	Refuse recipe	60
Hamoda *et al.*, 1998	MSW after hammer mill	60
Horisawa *et al.*, 2000	Rabbit food (alfalfa, flour, soybean and wheat germ) + sawdust	60
Morvan, 2009	MSW after rotary drum	54

Table 2.8. List of models other than Haug's (1993) for the description of the composting rate dependence on MC. All non-described parameters are empirical. (To be continued)

Reference	Moisture correction factor	Parameters definition	Model origin / use
Jeris & Regan, 1973b	$Y = ax^2 + bx + c$	Y - O_2 consumption rate (mmole/ day/g DM) x - moisture content (%, wet basis)	Developed from mixed refuse composting data.
Smith & Eilers, 1980, cited in Mason, 2006	$e^{\left[-10.973(FS-0.3)^2\right]}$	FS - solids fraction (dimensionless)	Developed from sludge composting data.
Cathcart *et al.*, 1986	$Y=a+bT+cH+dT^2+eH^2$	Y - composting rate (kg CO_2 generated/kg initial dry matter); T – temperature (ºC) H - moisture content (%, wet basis)	Developed from crab scrap + straw composting data.
Murwira *et al.*, 1990	WHC: 0-50% => $Y=0.02X - 0.0355$ WHC: 50-100% => $Y=0.0001X^2-0.032X + 2.179$	WHC - water holding capacity (%) Y - dry matter decomposition (mg C/g DM/d) X - moisture content (% of WHC)	Developed from cattle manure + sand composting data.
Stombaugh & Nokes, 1996; Sole-Mauri *et al.*, 2007	$kH_2O=0$ if $m_1 < m \le m_2$ $kH_2O=\frac{m}{m_2}-1.0$ if $m_2 < m \le m_3$ $kH_2O=1.0$ if $m_3 < m$	kH_2O - moisture coefficient m - moisture content (kg/kg wet basis) $m_1 = 0; m_2 = 0.2; m_3 = 0.4$	Stombaugh & Nokes, 1996 - equations are part of a composting model applied on trials with cracked corn and pelleted corn cobs; Sole-Mauri *et al.*, 2007 - equations are part of a model applied on trials with paper pulp, cattle manure and fruit pulp.
Mohee *et al.*, 1998	$f(m_c) = -56.97 + 57.9 \times e^{\left[(-0.5\times(m_c-0.56)/1.52)^2\right]}$	f(m_c) - factor to correct the first order reaction rate constant m_c - moisture content (%, wet basis)	Developed from experimental data of Smith & Eilers (1980)(cited in Mohee *et al.* (1998)), on activated sludge composting.
Ekinci *et al.*, 2001, cited in Ekinci *et al.*, 2006; Ekinci *et al.*, 2004, 2006; Keener *et al.*, 2003, 2005	$X_w = e^{-0.5[(w_c-a)/b)^2]}$	X_w - moisture correction factor for the first-order reaction rate constant (fractional) w_c - moisture content (%, wet basis)	Developed from experimental data on composting trials with paper mill sludge and broiler litter. Equation is part of a simulation model used by the authors.
Hamelers & Richard, 2001; Richard *et al.*, 2002	$OURm(\theta_w) = \frac{f(\theta_w, \varepsilon_s)}{f(\theta_{w,\max}, \varepsilon_{s,\max})} \times OUR\max$ $f(\theta_w) = \left(\frac{1-\varepsilon_s.(1+\theta_w)}{\theta_w.(1-\varepsilon_s)}\right)^n \times \left(\frac{\theta_w}{1+\theta_w}\right)^m$	$OUR_m(\theta_w)$ - maximum oxygen uptake rate at specific water content (mol O_2 $kg^{-1}h^{-1}$) OUR_{max} - maximum oxygen uptake rate in the water content range (mol O_2 $kg^{-1}h^{-1}$) $\theta_{w,max}$ - volumetric water content at which OUR_{max} occurs (m^3/m^3) $\varepsilon_{s,max}$ - volumetric solids content at which OUR_{max} occurs (m^3/m^3) n - exponent accounting for variation in tube dimensions (0<n<1) m - exponent accounting for effect of moisture on O_2 diffusion and microbial growth rate	Developed on a theoretical basis, in order to incorporate moisture effects on the mechanistic model of Hamelers (2001). Richard *et al.* (2002) applied this model on composting trials with manure and papermill sludge.

Table 2.8. List of models other than Haug's (1993) for the description of the composting rate dependence on MC. All non-described parameters are empirical. (Continuation)

Reference	Moisture correction factor		Parameters definition	Model origin / use
Kulcu & Yaldiz, 2004	$k_T = \frac{\frac{a}{Mc}}{T - C \times b} \times e^{(T \times c - d \times \frac{Mc}{T})}$		k_T - rate of decomposition (g VS/g VS day) T - temperature (ºC) Mc - Moisture content (%, wet basis) C - CO_2 production rate (%)	Developed from grass trimmings, tomato, pepper and eggplant composting data.
Xi *et al.*, 2005, 2008; Qin *et al.*, 2007	$k_{moisture} = 0$	$w<w_a$	$k_{moisture}$ - moisture content correction w - moisture content (%,wet basis) w_a - minimum moisture content (%, wet basis) w_1 - optimum moisture content (%, wet basis) w_2 - maximum moisture content (%, wet basis)	Developed from the author's experimental data. Equation is part of a composting model applied on experimental trials with domestic solid wastes.
	$k_{moisture} = \frac{w - w_a}{K_a + w}$	$w_a<w<w_1$		
	$k_{moisture} = \frac{w - w_a}{K_a + w} \times \frac{w_2 - w}{w_2 - w_1}$	$w>w_a$		
Bongochgetsakul & Ishida, 2008	$f_{H_2O} = \frac{\theta - \theta_{\min}}{\theta_{opt} - \theta_{\min}}$	$\theta_{\min} \le \theta \le \theta_{opt}$	f_{H2O} - water availability reduction factor (fractional) θ_{min} - minimum volumetric water content for microbial activity (m^3/m^3) θ_{opt} - optimum volumetric water content for microbial activity (m^3/m^3) θ_{max} - maximum volumetric water content for microbial activity (m^3/m^3)	Developed on a theoretical basis by the authors. Equation is part of a model applied on a theoretical exercise.
	$f_{H_2O} = \frac{\theta_{\max} - \theta}{\theta_{\max} - \theta_{opt}}$	$\theta_{opt} \le \theta \le \theta_{\max}$		
	$f_{H_2O} = 0$	elsewhere		
Yu *et al.*, 2009	$k_w = 0.0$ $k_w = 5.0 \times MC - 1.0$ $k_w = 1.0$	MC<0.2 0.2<MC<0.4 0.4<MC	k_w - moisture correction factor for the first-order reaction rate constant MC - moisture content (decimal, wet basis)	Equation proposed by the authors. Its is part of a composting model applied on experimental trials with dairy manure and straw.

2.2.5 Correction factor for free air space – F(FAS)

Compared with the other factors (T, MC or $[O_2]$), modelling of the effect of the free air space (FAS) on the composting reaction rate has been much less explored by the composting research community. The model equation used by Haug (1993), which will be adopted here, is the following (equation 2.26, figure 2.7):

$$F(FAS) = \frac{1}{e^{(-23.675\,FAS + 3.4945)} + 1} \tag{2.26}$$

where FAS is the fractional free air space of the composting material.

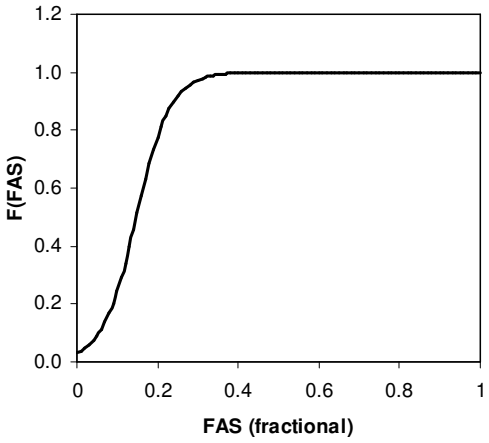

Figure 2.7. Correction factor for FAS, F(FAS) (equation 2.26), adopted in this work.

Haug (1993) based this model on the same data used for the definition of F(MC) and, additionally, on data collected by Jeris & Regan (1973a) for several types of composting materials, which shows that the optimum FAS is generally about 30%.

Other work where Haug's (1993) FAS correction factor was used include Bertoni *et al.* (1997), Tollner *et al.*, (1998), Kim *et al.* (2000), Ndegwa *et al*. (2000), Li *et al.* (2002), Cronjé *et al.* (2004), Xi *et al.* (2005) and Petric & Selimbasic (2008).

Another model studying the effect of the FAS on the composting reaction rate was found in the literature (Yu *et al.*, 2009). This model has a similar graphical form to the one defined by Haug (1993), but it was calibrated for a different type of material - fresh dairy manure and straw mixed with other materials (equations 2.27 and 2.28).

In the mesophilic range (0 – 55ºC): $k_{\max}^{meso} = 0.01 + 0.90 \times e^{-e^{-15.0(FAS - 0.53)}}$ (2.27)

In the thermophilic range (40 – 75ºC): $k_{\max}^{thermo} = 0.01 + 0.70 \times e^{-e^{-12.3(FAS - 0.55)}}$ (2.28)

Nevertheless, the effect of FAS has been implicitly included in several models which describe the effect of MC on the reaction rate (Smith & Eilers, 1980, cited in Mason, 2006; Murwira *et al.*, 1990; Stombaugh & Nokes, 1996; Mohee *et al.*, 1998 Ekinci *et al.*, 2001, cited in Ekinci *et al.*, 2006; Ekinci *et al.*, 2004; Hamelers & Richard, 2001; Richard *et al.*, 2002; Keener *et al.*, 2003, 2005; Xi *et al.*, 2005, 2008; Qin *et al.*, 2007; Bongochgetsakul & Ishida, 2008). In these models, reaction rate increases with increasing moisture content but, above a certain moisture level, reaction rate decreases again. This decrease in reaction rate at high moisture levels is caused by a decrease in FAS, which in turn creates oxygen supply limitations. These models are actually equivalent to the summation of the F(MC) and F(FAS) factors used in this work, as the variation pattern with MC is similar in both cases.

2.2.6 Initial biodegradable volatile solids content - [BVS_o]

Initial biodegradable volatile solids content ([BVS_o]), i.e., biodegradability, provides very important information for process design and operation, as it is essential in order to close mass and energy balances (Haug & Ellsworth, 1991; Haug, 1993). In practice, for the purposes of this study, biodegradability determinations should provide information about the upper limit in VS consumption that could be achieved, in the time scale of the processes in study, if the conditions for composting were optimized.

Biodegradability depends on the composition of waste and on the degradation conditions (Haug & Ellsworth, 1991; Kayhanian, 1995), and it has been correlated to the lignin content of the waste, both in anaerobic (Chandler *et al.*, 1980; Kayhanian, 1995) and in aerobic conditions (Komilis & Ham, 2003), because lignin is very recalcitrant to biological degradation (Kirk & Farrell, 1987; Tuomela *et al.*, 2000).

Biodegradability must be determined experimentally but, to our knowledge, there is, as yet, no standardized method for the determination of biodegradability in normal composting conditions. Its determination can be made from VS losses in medium to long-term composting experiments (Adani *et al.*, 2000; Minkara *et al.*, 1998; Sesay *et al.*, 1998; Fricke & Mueller, 1999; Zach *et al.*, 2000; Lasaridi & Stentiford, 2001; Lornage *et al.*, 2007), or by respirometric techniques, measuring total oxygen consumption or total carbon dioxide production, either in liquid medium (Haug & Ellsworth, 1991; Boni & Musmeci, 1998; Barrena *et al.*, 2009) or in a solid matrix (Pagga *et al.*, 1995; Atkinson & Jones, 1996; Komilis & Ham, 2000, 2006; Adani *et al.*, 2001; Tremier *et al.*, 2005; Eklind *et al.*, 2007; Scaglia & Adani, 2008; Tosun *et al.*, 2008; Mason, 2009).

Therefore, for the purposes of this study, VS consumption data from similar materials to the ones studied here (MSW / biowaste), in sufficiently long term full / pilot / lab-scale experiments (table 2.9), was used to estimate the [BVS_o] value for the simulations.

Table 2.9. Biodegradable volatile solids contents, relative to the total VS content, collected from the bibliography for [BVS_o] estimation. All data came from VS measurements.

Reference	Material	System description	Study scale	RT*** (d)	[BVS_o] (rel. Vs)
Sesay *et al.*, 1998	Scottish MSW treated in a rotating drum for 6 h, then sieved at 50 mm	Static pile with hybrid aeration system, one mixing over the 51 d; 10 tons test	Pilot	51	0.61**
Fricke & Muller, 1999	German MSW treated in a rotating drum for 12-20 h, then sieved under 40 mm	HV 1-1: Open air process; 8 weeks high-rate composting; 43 weeks curing in unventilated. static piles	Full	56+288	0.71*
	German MSW treated in a rotating drum for 12-20 h, then sieved under 40 mm	HV 2: Open air process; 16 weeks high-rate composting; 45 weeks curing in unventilated, static piles		112+320	0.70*
	German MSW treated in a rotating drum for 12-20 h, then sieved under 40 mm	HV 3: Open air process; 4 weeks high-rate composting; 57 weeks curing in unventilated, static piles		28+404	0.56*
	German MSW treated in a rotating drum for 12-20 h, then sieved under 40 mm	ROCO4: Closed container, high control system; 18 weeks high-rate composting		129	0.62*
	German MSW	Kessler & Luch - forced aeration system		78	0.57*
Adani *et al.*, 2000	Italian MSW treated mechanically; fraction<50 mm	First 37 d - continually aerated windrow; turning every 2 days; then curing phase	Full	37+79	0.57**
		First 37 d - composting in a 150 l adiabatic reactor, with forced aeration; then 79 d in a non-ventilated heap, turned every 4 to 5 d; with water addition; 26 Kg sample	Lab	37+79	0.66**
Lornage *et al.*, 2007	French MSW	Windrow with positive forced aeration; 37.5 tons test	Pilot	175	0.62**
Mean value					**0.62**

* Information from the authors digitized and used to estimate [BVS_o] values by fitting with the simulation model adopted in this work (sections 4.2.1 and 4.2.6).
** Values correspond to the total VS loss in the period of the study.
***RT stands for residence time. When two time periods are presented, the first corresponds to the high rate composting phase, the second to the cure phase.

The average [BVS_o] is 0.62 (or 62%, in relation to the total VS content), as calculated from the values presented in table 2.9, and will be adopted in this work for the estimation of the reaction rate constants (k) from the experimental data. In some situations, though, which will be indicated in the text, the [BVS_o] value will not be fixed at 0.62, and will be estimated by the model, together with the k value (section 5.3).

It should be mentioned that the residence times (RT) in some of the studies listed in table 2.9 (presented in the form "xx + xx") are very long in relation to the time scale of the processes studied in this work. However, it must be noted that the first RTs (before the "+") correspond to the high-rate composting phases, whereas the second RTs (after the "+"), which are the longest, relate to the curing phases, where the process usually proceeds at a much slower rate, due to poor process control. Therefore, it was considered that the data in table 2.9 is representative for [BVS_o] estimation, for the purposes of this work.

Other data collected, which was not used in the estimation of the [BVS_o] value, but which can somehow be considered for comparison purposes, is presented in the tables 2.10 and 2.11.

Inspection of table 2.10 indicates that the [BVS_o] values obtained from composting experiments with similar materials to the ones studied in this work do not vary much in relation to the reference value chosen here, i.e., 0.62. However, the results for biowaste studies seem to indicate that the [BVS_o] for this material is higher than for MSW. Data from Eklind & Kirchmann (2000) and Komilis & Ham (2000) lead to higher [BVS_o] values than the one estimated here for MSW. Data from Beck-Friis *et al.* (2001, 2003) and Smars *et al.* (2002) lead to values in the range of the one estimated here, but in relatively short process times. The lower [BVS_o] value for MSW may be due to the presence of paper in significant amounts in this material. In fact, results from Komilis & Ham (2000) indicate that paper has a lower [BVS_o] than food waste (cf. table 2.11).

Regarding yard waste, this is a component that may be present in biowaste and MSW in varying weights, which could cause a variation in [BVS_o]. However, [BVS_o] values for yard waste are probably in the same range as for the material studied in this work (table 2.11).

It is felt that the definition of a standardized method for the determination of biodegradability in normal composting conditions is important. However, as biodegradability depends on the degradation conditions (Haug & Ellsworth, 1991; Kayhanian, 1995), the problem is the definition of "normal composting conditions", because these will be determinant for the result.

Table 2.10. Biodegradable volatile solids contents, relative to the total VS content, for waste materials similar to the ones studied here. This data was not used for [BVS_o] estimation, but it is presented, for comparison purposes. (To be continued)

Reference	Material	Composting system	Scale of the study	RT (d)	[BVS_o] (rel. VS)	Sort of data
Haug, 1993	Food waste	-	-	-	0.6	-
Boni & Musmeci, 1998	Organic fraction of MSW	Aerobic biodegradability test in liquid medium, at 22ºC for 28 days	Lab	28	0.68**	C-CO_2 emissions
Namkoong *et al.*, 1999	Food waste recipe - 15% cereals, 50% vegetables; 20% meat or fish; 15% fruits + 5% wet weight mature compost	2 l beakers at 25ºC, MC: 50-60%; daily mixing, no aeration	Lab	80	0.65*	VS
	Food waste recipe - 30% cereals, 41% vegetables; 17% meat or fish; 12% fruits + 5% wet weight mature compost				0.78*	
	Food waste recipe - 11% cereals, 38% vegetables; 40% meat or fish; 11% fruits + 5% wet weight mature compost				0.51*	
Eklind & Kirchmann, 2000	Food waste recipe (65% potatoes + 15% carrots + 13% meat meal + 7% bone meal)	125 l insulated bins, rotable around the horizontal axis, with ventilation holes on the sides; daily turning of material; on day 177, compost was removed from the reactor, placed in open plastic bags at about 17ºC, and left until day 590	Lab	590	0.88**	VS
	Food waste recipe (65% potatoes + 15% carrots + 13% meat meal + 7% bone meal) : (Paper); 4.18:4.06 (dry matter basis)				0.64**	
Komilis & Ham, 2000	Food waste recipe (Milk + cooked pasta + hamburger + lettuce + raw potatoes + carrots in equal amounts (wet weight basis))	25 l lab reactors at 55ºC, with forced aeration	Lab	91	0.69**	Total organic Carbon

* Information from the authors digitized and used to estimate [BVS_o] values by fitting with the simulation model adopted in this work (sections 4.2.1 and 4.2.6).
** Values correspond to the total VS loss in the period of the study.

Table 2.10. Biodegradable volatile solids contents, relative to the total VS content, for waste materials similar to the ones studied here. This data was not used for [BVS_o] estimation, but it is presented, for comparison purposes. (Continuation)

Reference	Material	Composting system	Scale of the study	RT (d)	[BVS_o] (rel.VS)	Sort of data
Scaglia *et al.*, 2000	Biowaste : green waste; 2:1 on a wet basis	Full-scale composting plant - first phase in air tunnel for 30 d, second treatment phase for 2 months	Full	90	0.72**	VS
	Biowaste + Wood				0.63**	
Beck-Friis *et al.*, 2001	Household source separated waste triturated (<13 mm) : chopped wheat straw; 1:0.3 (dry weight basis)	Insulated 200 l reactor, with aeration, daily semi-manual mixing	Lab	21-30	0.64*	C-CO_2 emissions
Smars *et al.*, 2002	Household source separated waste triturated : chopped wheat straw; 3:1 (dry weight basis)	Insulated 200 l reactor, with aeration, daily semi-manual mixing	Lab	15	0.64*	C-CO_2 emissions
Beck-Friis *et al.*, 2003	Household source separated waste triturated (<13 mm) + chopped wheat straw	Insulated 200 l reactor, with aeration, daily semi-manual mixing	Lab	25	0.62*	C-CO_2 emissions
Komilis & Ham, 2003	MSW recipe (with mixed paper/yard waste/food waste)	25 l lab reactors at 55ºC, with forced aeration	Lab	170	0.70**	DM
	MSW recipe (with mixed paper:yard waste:food waste; 1:1:1)			47	0.67**	
Eklind *et al.*, 2007	Household source separated waste triturated (<13 mm) + chopped wheat straw	Insulated 200 l reactor, with aeration, daily semi-manual mixing	Lab	15	0.58*	C-CO_2 emissions

* Information from the authors digitised and used to estimate [BVS_o] values by fitting with the simulation model adopted in this work (sections 4.2.1 and 4.2.6).
** Values correspond to the total VS loss in the period of the study.

Table 2.11. Biodegradable volatile solids contents, relative to the total VS content, for paper and yard waste. This data was not used for [BVS_o] estimation, but it is presented, for comparison purposes.

Reference	Material	Composting system	Scale of the study	RT (d)	[BVS_o] (rel. VS	Sort of data
Komilis & Ham, 2000	Mixed paper, corrected for a C/N of 25-30	25 l lab reactors at 55ºC, with forced aeration	Lab	198	0.38**	Total organic carbon
Haug, 1993	Yard waste	-	-	-	0.60	-
Michel & Reddy, 1998	Yard trimmings (leaves:grass; 2:1)	Composting in 4 l reactors, with forced aeration	Lab	40	0.46*	C-CO_2 emissions
Komilis & Ham, 2000	Yard waste (Grass clippings : leaves; 1.5:1 (dry weight basis))	25 l lab reactors at 55ºC, with forced aeration	Lab	69	0.62**	Total organic carbon

* Information from the authors digitized and used to estimate [BVS_o] values by nonlinear regression, using the simulation model adopted in this work (sections 4.2.1 and 4.2.6).
** Values correspond to the total VS loss in the period of the study.

2.2.7 Complete model

In summary, the model adopted in this work to describe the kinetics of the composting process is defined as follows (equation 2.29):

- First-order reaction rate equation, dependent on [BVS] (Haug, 1993);
- Kinetic rate constant corrected for T, MC, [O_2] and FAS (Haug, 1993);
- Reaction rate dependence on T described by the model of Rosso *et al.* (1993); equation parameters estimated by Richard (1997) and Richard & Walker (1999, 2006);
- Reaction rate dependence on [O_2] described by Monod equation, according to Richard (1997), Richard & Walker (1999) and Richard *et al.* (2006); K_{O_2} estimated from these authors' data;
- Reaction rate dependence on MC and FAS defined according to Haug (1993);
- [BVS_o] estimated at 0.62 from data collected from several sources in the literature.

$$VS\ consumed_t = [BVS_o].(1 - e^{-k \times F(T) \times F(MC) \times F(O_2) \times F(FAS) \times t})$$

(2.29)

where

$[BVS_o]= 0.62$

$$F(T) = \frac{(T - 71.6)(T - 5)^2}{(58.6 - 5)\left[(58.6 - 5)(T - 58.6) - (58.6 - 71.6)(58.6 + 5 - 2T)\right]}$$

$$F(MC) = \frac{1}{e^{(-17.684(1-DM)+7.0622)} + 1}$$

$$F(O_2) = \frac{[O_2]}{F_{O_2}(20.95\%) \times (0.83 + [O_2])} \quad \text{with} \quad F_{O_2}(20.95\%) = \frac{20.95}{0.83 + 20.95}$$

$$F(FAS) = \frac{1}{e^{(-23.675FAS+3.4945)} + 1}$$

This model allows the description of the kinetics of the composting process with measurable data.

One underlying assumption in this modelling approach is that the environmental correction factors (F(T), T(MC), F([O2]) and F(FAS)) are independent from each other. This is common practice in composting modelling (Haug, 1980, 1993; Stombaugh & Nokes, 1996; Bertoni *et al.*,1997; Tollner *et al.*, 1998 ; Kim *et al.*; 2000; Ndegwa *et al.*; 2000; Higgins & Walker, 2001; Li *et al.*, 2002; Keener *et al.*, 2003, 2005; Cronjé *et al.*, 2004; Bongochgetsakul & Ishida, 2008; Petric & Selimbasic, 2008; Xi *et al.*, 2008; Yu *et al.*, 2009). However, it should be mentioned that Hamelers (2001, 2004) argued that this may not be true, and there are also experimental results that indicate the same. Richard & Walker (1999, 2006) obtained results showing that optimal temperature varies, depending on moisture content, oxygen content and type of material. Moreover, Richard *et al.* (2006) have shown that the composting rate dependence on $[O_2]$ varies according to the T and MC conditions. Hamelers & Richard (2001) have also shown theoretically that optimum MC may change during the composting process.

3. CASE STUDIES

This chapter presents a general description of the four MBT plants studied in this work.

3.1 MBT1 – Mechanical-biological treatment plant 1

General data

Input waste: Municipal solid waste (MSW)

Waste treatment capacity (nominal / real): 150 000 / 170 000 tons per year

Plant and processes description

Pre-treatment

- MSW reception area;
- Manual sorting of large items (directed to landfill);
- 2 sieves at 120 mm;
- Manual sorting for cardboard in the fraction > 120 mm (for recycling);
- 2 overbands for the fraction < 120 mm (iron is separated, for recycling);
- 2 sieves at 80 mm for the fraction < 120 mm – Iron;
- Compaction of the fractions > 120 mm and 80 to 120 mm (for landfill);
- Fraction <80 mm – Iron proceeds for biological treatment in the composting park.

Composting

- Input: stream < 80 mm - Iron;
- System: positive ventilation windrows;
- Aeration: performed by 4 blowers;
- Material turning frequency: every 6.3 days;
- Technology: Koch, with 2 composting parks (the one studied was the North park);
- Retention time: approximately 9.0 weeks (63 days);
- Building: closed;
- Pile height: approximately 1.5 m;
- Water addition to the composting material: can be done by the turning machine, during the turning operations, but it is not performed.

Post-treatment

- A double sieve, oblong holes 8 by 20 mm at the beginning, oblong holes 20 by 40 mm at the end (refuse goes to landfill);
- 1 densimetric table for the fraction 8x20 to 20x40 mm and 2 densimetric tables for the fraction < 8x20 mm (refuse directed to landfill);
- Compost is used in agriculture.

The plant is schematised in figure 3.1.

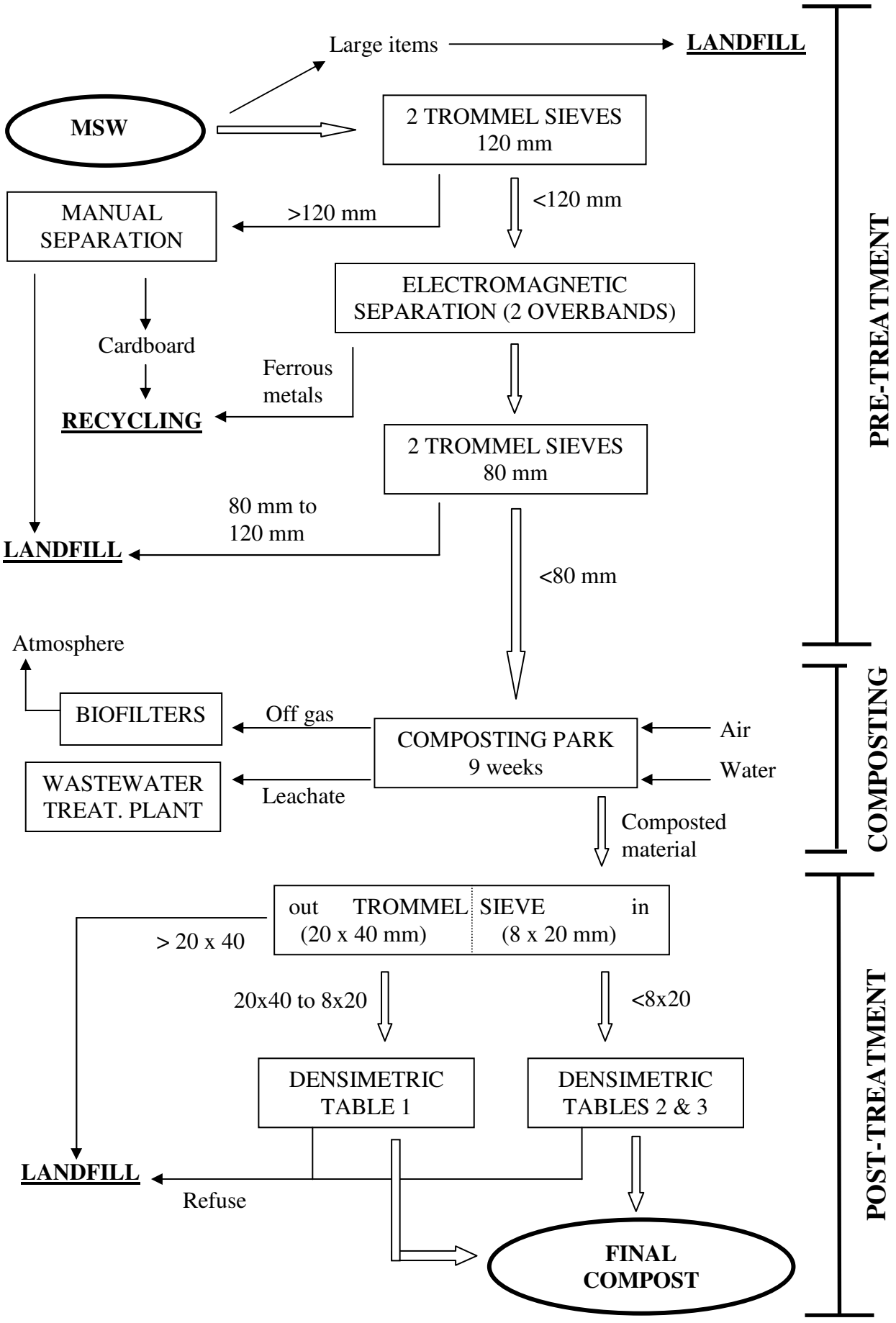

Figure 3.1. Schematic diagram of MBT1.

3.1.2 MBT2 – Mechanical-biological treatment plant 2

General data

Input waste: MSW

Waste treatment capacity (nominal / real): 87 600 / 160 000 tons per year

Plant and processes description

Pre-treatment

- MSW reception area;
- Manual sorting of large items (directed to landfill);
- 2 rotary drums, 4.2 m in diameter and 40 m long each, one rotation per minute; retention time: approximately 1 day (24 hours);
- 2 trommel sieves of 25 mm; fraction > 25 mm is directed to landfill; fraction < 25 mm proceeds for biological treatment in the composting park.

Composting

- Input: stream < 25 mm;
- System: negative aeration windrows;
- Aeration: performed by 11 blowers; zone 1 is not ventilated;
- Material turning frequency: every 7 days;
- Technology: Vinci Environment; Windrows are turned with a RAC (Retourneur Automatique d'Andain); 1 composting park;
- Retention time: approximately 7.0 weeks (49 days);
- Building: closed;
- Pile height: approximately 2.5 m;
- Water addition to the composting material: can be done by the turning machine, during the turning operations, but it is not performed.

Post-treatment

- 1 trommel sieve with round holes of 15 mm;
- 2 densimetric tables for the fraction < 15 mm;
- Fraction > 15 mm and heavy refuse from the densimetric tables goes to landfill;
- Compost is used in agriculture.

A diagram of the plant is shown in figure 3.2.

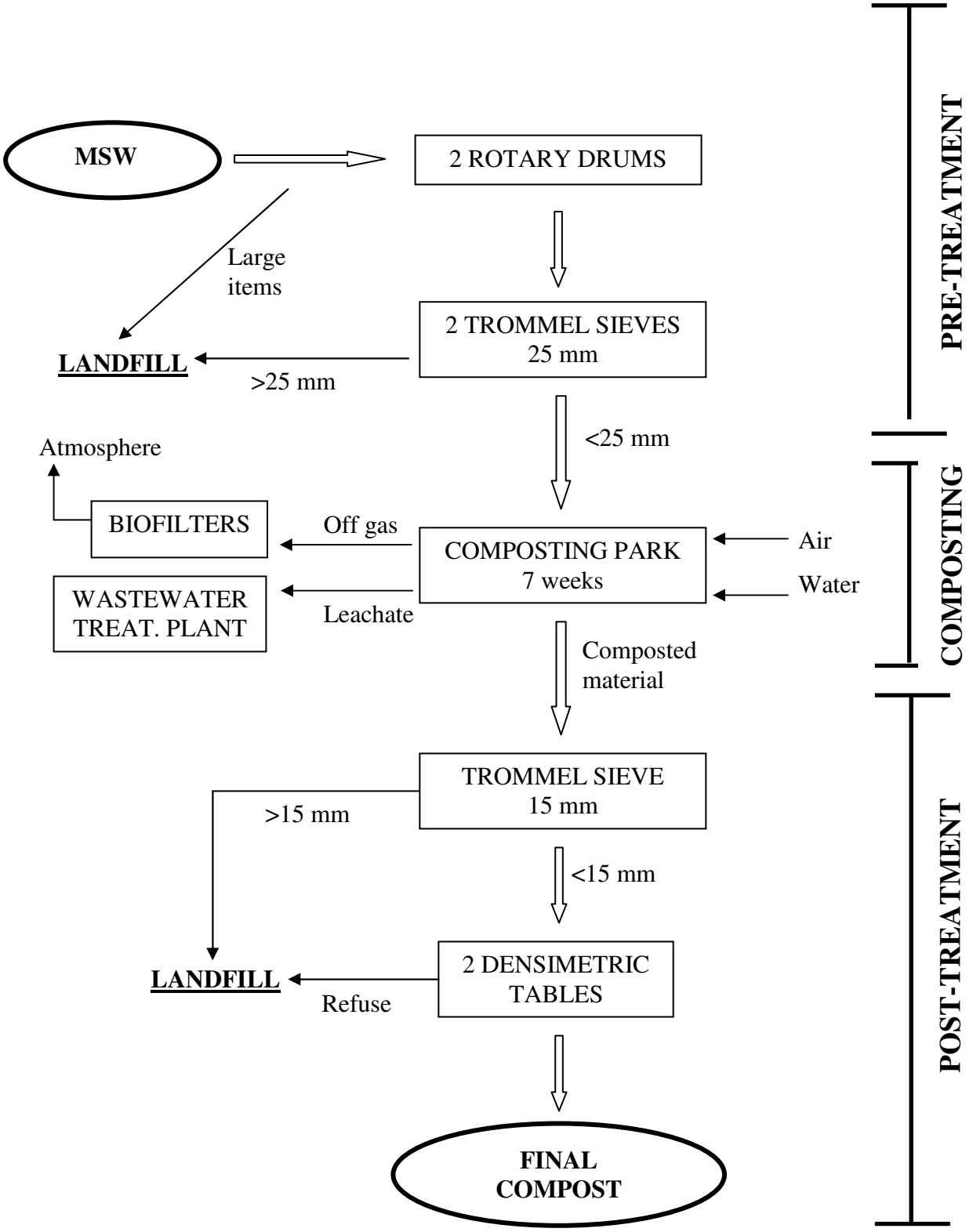

Figure 3.2. Schematic diagram of MBT2.

3.1.3 MBT3 – Mechanical-biological treatment plant 3

General data

Input waste: Municipal solid waste (MSW)

Waste treatment capacity (nominal / real): 50 000 / 50 000 tons per year

Plant and processes description

Pre-treatment

- MSW reception area;
- Manual sorting of large items (directed to landfill);
- 1 sieve at 120 mm;
- Manual sorting for cardboard and plastic in the fraction > 120 mm;
- 1 overband for the fraction < 120 mm (iron goes for recycling);
- 1 sieve at 80 mm for the fraction < 120 mm - Iron;
- 1 overband for the fraction < 80 mm (iron goes for recycling);
- 1 Focault separator for the fractions > 120 mm and 80 to 120 mm (aluminium is directed to recycling);
- Compaction of the fractions > 120 mm and 80 to 120 mm (directed to landfill).

Composting

- Input: stream < 80 mm - Iron;
- System: positive aerated windrows;
- Aeration: performed by 1 blower;
- Material turning frequency: every 6 days;
- Technology: Koch, with 1 composting park;
- Retention time: approximately 8.5 weeks (59.5 days);
- Building: closed;
- Pile height: approximately 1.5 m;
- Water addition to the composting material: performed by the turning equipment, during the turning operations, until zone 9.

Post-treatment

- 1 flip-flow sieve for the composted material (12 mm);
- 1 densimetric table for the fraction <12 mm;
- Fraction > 12 mm and heavy refuse from the densimetric table goes to landfill;
- Compost is used in agriculture.

A diagram of the plant is shown in figure 3.3.

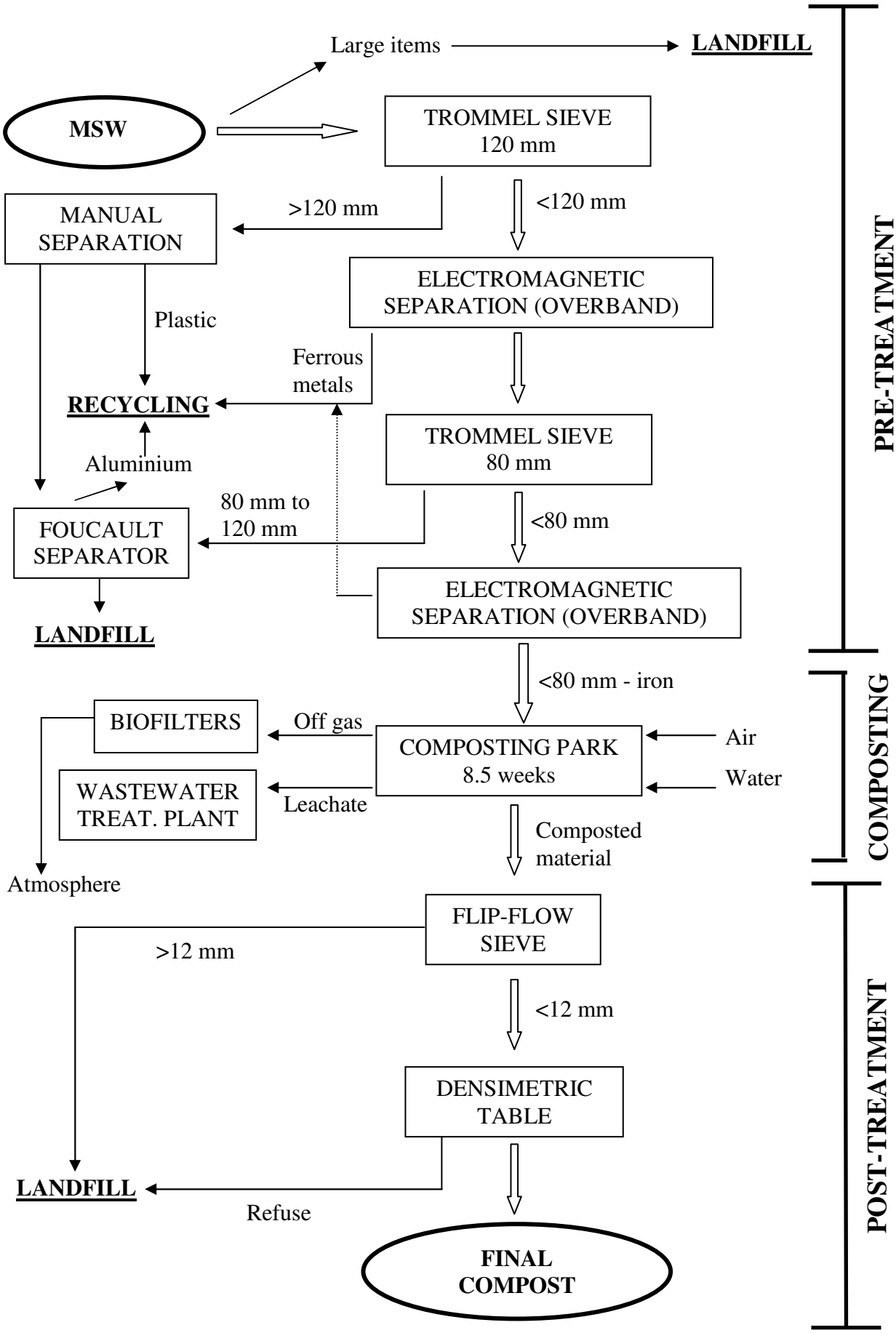

Figure 3.3. Schematic diagram of MBT3.

3.1.4 *MBT4 – Mechanical-biological treatment plant 4*

General data

Input waste: MSW

Waste treatment capacity (nominal / real): 50 000 / 100 000 tons per year

Plant and processes description

Pre-treatment

- MSW reception area;
- Manual sorting of large items (directed to landfill);
- 1 trommel sieve with two sieving sizes: 150 mm and 75 mm;
- Manual sorting for cardboard and plastic in the fraction > 150 mm (for recycling);
- 1 trommel sieve at 75 mm for the fractions < 150 mm – iron and 75-150 mm;
- 1 overband for the fraction < 75 mm (iron is separated, for recycling);
- Fraction > 75 mm directed to landfill;
- Fraction (<75 mm – iron) proceeds for biological treatment in the composting park.

Composting

- Input: stream < 75 mm - iron;
- System: negative aeration windrows;
- Aeration: performed by 2 blowers;
- Material turning frequency: every 2 days;
- Technology: Siloda, with 6 composting bays
- Retention time: approximately 12 days;
- Building: closed;
- Pile height: approximately 1.5 m;
- Water addition to the composting material: can be done by the turning machine, during the turning operations, but it is not performed.

Post-treatment

- 1 trommel sieve with round holes of 30 mm;
- 1 densimetric table for the fraction < 30 mm;
- Light fraction (compost) from the densimetric table is milled in a grinder, and sieved in a trommel sieve at 12.5 mm;
- Fractions > 30 mm (from the first sieve), >12.5 mm (from the second sieve) and heavy refuse (from the densimetric table) are disposed to landfill;
- Compost is used in agriculture.

The plant is schematised in Figure 3.4.

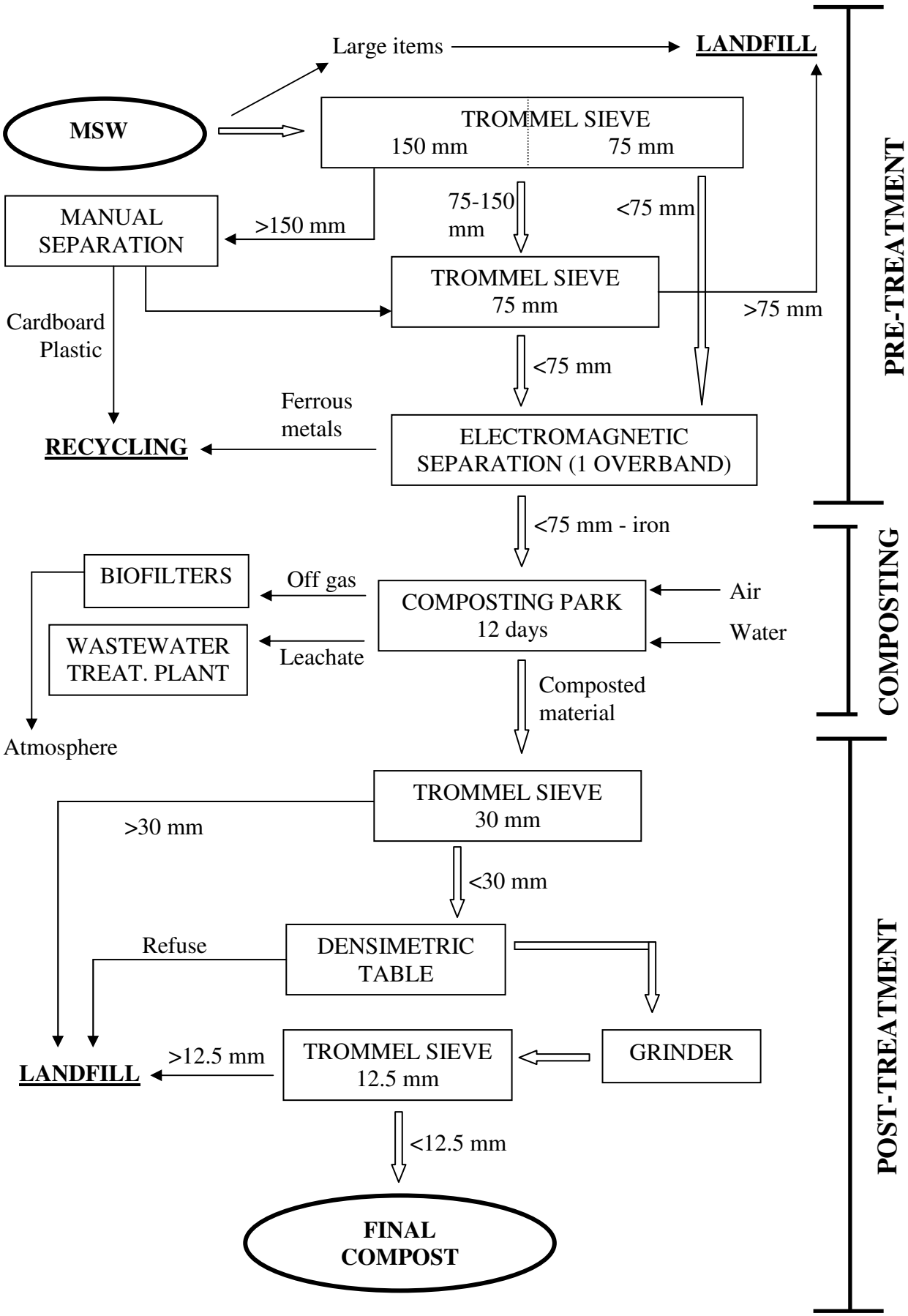

Figure 3.4. Schematic diagram of MBT4.

3.1.5 Relevant aspects

Analysis of the information given for the four plants shows that MBT1 and MBT3 are very similar. In fact, the technology supplier in these plants is the same. There are some minor variations in the configuration, but these plants are equivalent. One major difference concerns the plant nominal capacity, which is three times larger in MBT1 than in MBT3.

In terms of MSW pre-treatment, MBT4 is equivalent to MBT1 and MBT3, the main difference being the sieving size for the fraction which proceeds for composting – 75 mm in MBT4, 80 mm in MBT1 and MBT3. In all these three plants, MSW pre-treatment involves mainly sieving operations and magnetic separation of ferrous metals, without much MSW particle size reduction. Concerning MBT2, it presents a substantially different pre-treatment system. This is mainly due to the presence of two rotary drums, which have a significant effect in reducing the size of the MSW particles (Aboulam *et al.*, 2006). As a consequence, a smaller sieve for the fraction for composting can be used in relation to the other plants, which is 25 mm in this case.

Regarding the composting technology, again this is very similar in MBT1 and MBT3. The residence times of the material in the composting parks are also similar, being around 63 days in MBT1 and 59.5 days in MBT3, as well as the material turning frequency (6.3 and 5.95 days, respectively). In MBT2, the turning machine is slightly different, mainly because it has a larger mechanical action in the composting material, i.e., it is more effective in reducing the size of the composting particles. However, the turning frequency (7 days) and the residence time in the composting park (around 49 days) are similar to MBT1 and MBT3. It should be mentioned that the real capacity of MBT2 is more than twice its nominal capacity. The residence time in the composting park is not much affected, though, which means that the height of the composting piles is quite large in this plant, around 2.5 metres, whereas in the other plants it is around 1.5 metres. Concerning MBT4, composting process management is significantly different than in any of the other plants. The composting technology can be considered as equivalent, namely to MBT1 and MBT3 technology, but residence time is much smaller (around 12 days), as well the material turning frequency (around 2 days). These differences are caused partly by the fact that the plant is operated at double its nominal capacity.

Concerning the post-treatment, this is equivalent in the four plants. Post-treatment aims at removing contaminant materials from the composted product, like glass and plastic, and is part of all the plants studied, as the final compost is used for agricultural purposes.

Some pictures of the plants are presented in figures 3.5-3.10.

Figure 3.5. Two rotary drums for MSW pre-treatment.

Figure 3.6. Composting park with turning machine.

Figure 3.7. Composting bays with turning machine.

Figure 3.8. Turning machine.

Figure 3.9. Turning machine.

Figure 3.10. Blower for forced aeration.

4. MATERIALS AND METHODS

4.1 Experimental data collection

The second action of this work was to develop and implement an expeditious procedure for collection of experimental data from the MBT plants under study, in order to feed the simulation model. This procedure is presented in this section.

4.1.1 Time period

Experimental data collection in the four MBT plants studied was carried out in the period from April 2002 to February 2003.

4.1.2 General procedures

Data collection was carried along the composting process for volatile solids (VS) content, temperature (T), moisture content (MC), oxygen concentration in the free air space ($[O_2]$), and free air space (FAS), in the four MBT plants. The output composted material was analyzed with the self-heating test (FCQA, 1994). This way, profiles were obtained for VS content, T, MC, $[O_2]$ and FAS *versus* process time. For this purpose, physical zones had to be defined along the composting process, in which measurements were made. Six to ten zones were considered, depending on each MBT configuration, which are relatable to process time (table 4.1).

Table 4.1. Number of zones considered in each MBT plant in study.

MBT	Number of zones
1	10
2	7
3	10
4	6

Sampling for the assessment of each of the parameters mentioned above was performed with the guidelines of CEN (European Committee for Standardization) standard "Sampling of liquid and granular waste materials including paste-like materials and sludges", parts 1- 5, which was at the time of sampling under final preparation (CEN, 2001). Each solid sample had around 30 to 40 litters, and was collected from three points in the pile, after removing the top layer of the composting material. From each of those sampling points, two to three full-shovels (normal bricklayer shovel with 30 by 30 cm) were taken. The sampled material was then thoroughly mixed and successively divided until getting to the desired subsample size.
Some pictures of the waste materials and of the data collection operations are presented in figures 4.1 - 4.6.

Figure 4.1. MSW after pre-treatment.

Figure 4.2. Composted material after post-treatment.

Figure 4.3. Sampling in a composting park.

Figure 4.4. Sampling in a composting park.

Figure 4.5. Samples collected for analysis.

Figure 4.6. Measuring oxygen concentration.

4.1.3 Temperature

Temperature was measured using stainless steel temperature probes. These were 1.5 m long and were built with a stainless steel tube with 10 mm external diameter and 6 mm internal diameter. Semiconductor LM35 monolithic temperature sensors were used. Each probe had

two sensors, one located on the pointed extremity of the probe, and the other 0.5 m from the former. The conditions used in each of the four MBT plants studied are indicated in table 4.2.

Table 4.2. Details on T data collection.

	MBT1	MBT2	MBT3	MBT4
Number of sets of measurements*	10	3	1	15
Number of points per zone	6	6-10	10	6 - 9
Number of measurements per point	1	1	1	1
Depth(s) of measurement (m)**	0.5; 1	1	0.5; 1	1

* Each set of measurements, for the whole composting park, was made in one day. No more than one set of measurements was made in one day.

** From the top.

4.1.4 Water and volatile solids contents

A sub-sample of 2 kg was placed in two aluminium trays, with no further treatment. Water content was determined by drying at 105 ºC (FCQAO, 1994) in a drier (Memmert, model 800) until constant mass.

The dried material was then burnt in the aluminium trays, using ethanol, in order to reduce the calorific potential of the samples. The trays then proceeded to an 80 l furnace (Barracha, model KD-4), where they were kept at 550 ºC (FCQAO, 1994) until constant mass for loss on ignition determination (volatile solids content). This procedure was applied to all the four plants studied, as described in table 4.3.

Table 4.3. Details on MC and VS contents data collection.

	MBT1	MBT2	MBT3	MBT4
Number of sets of measurements*	1	1	1	2
Number of samples collected per zone	5	3	5	3 - 6
Number of MC and VS contents determinations per sample	2	2	2	2

* Each set of measurements corresponded to the whole composting park.

4.1.5 Oxygen concentration

Oxygen concentration in the free air space of the composting material was measured using a gas analyser (Geotechnical Instruments, model GA2000), and air sampling probes in stainless steel (1.5 m long). The probes were built with a stainless steel tube with 10 mm external diameter and 6 mm internal diameter, perforated in the extremity that is put in the waste. The conditions used in each of the four composting plants studied are listed in table 4.4.

Table 4.4. Details on [O_2] data collection.

	MBT1	MBT2	MBT3	MBT4
Number of sets of measurements*	10	3	1	5
Number of points per zone	6	5 - 10	6	2 - 10
Number of measurements per point	1	1	1	1
Depths of measurement (m)**	1	1	1	1

* Each set of measurements, for the whole composting park, was made in one day. No more than one set of measurements was made in one day.

** From the top.

4.1.6 Total bulk density

The BD was determined according to Thompson *et al.* (2002), method 03.01-C, which involved the use of a 20 litter container. The container is consecutively filled up until one-third, two-thirds and full capacity. After each filling operation, there is a compaction step, in which the container is left to fall ten times in a hard surface from a height of approximately 15 cm. The container is then filled up to its full capacity, and the total weight of composting material is measured. The following conditions were used for each of the four plants studied (table 4.5).

Table 4.5. Details on BD data collection.

	MBT1	MBT2	MBT3	MBT4
Number of sets of measurements*	1	1	1	1
Number of samples collected per zone	5	3	5	3 - 5
Number of BD determinations per sample	1	1	1	1

* Each set of measurements corresponded to the whole composting park.

4.1.7 FAS calculation from total bulk density data

FAS was calculated from the total bulk density obtained according to Thompson *et al.* (2002), method 03.01-C, and the MC ([DM]=1-MC) and VS results (section 5.1, appendix A), together with particle densities, according to the following equation (Richard *et al.*, 2002):

$$FAS = 1 - BD \times \left[\frac{(1-[DM])}{\ell_w} + \frac{[DM]\times[VS]}{\ell_{VS}} + \frac{[DM]\times(1-[VS])}{\ell_{ash}} \right] \quad (4.1)$$

where

FAS - free air space (air-filled porosity) (fractional)

BD - total bulk density on a wet basis (kg/m^3)

ℓ_w - water density (kg/m^3)

ℓ_{ash} - particle density for the inorganic fraction (ash) (kg/m^3)

ℓ_{VS} - particle density for the volatile fraction (kg/m^3)

[DM] – dry matter content (fractional)

[VS] – volatile solids content (fractional)

BD, [DM] and [VS] are experimental results from the present work. A value of 0.99821 g/cm^3 was assumed for ℓ_w , which is the water density at 20ºC (Lide & Frederikse, 1995). ℓ_{ash} and ℓ_{VS} will be assumed to equal 2.5x10^3 and 1.6x10^3 kg/m^3, respectively (Richard *et al.*, 2002).

4.1.8 Self-heating test

The self-heating test for the determination of the degree of rotting gives an indication of the degree of stabilisation of organic matter in the composted material. This test was done according to the method described in FCQAO (1994), for the final compost, already after post-treatment (refining). It was performed for the four MBT plants in triplicate.

The calculation and the evaluation of the results are based on the maximum temperature reached during the self-heating test of the compost introduced in the Dewar vessels, which was recorded on a hourly basis. The stabilization degree (also named degree of Rotting) of compost varies from Class I (fresh organic matter) to V (well stabilized compost) according to the maximum temperature value reached, as indicated in table 4.6.

Table 4.6. Definition of the degree of Rotting according to the maximum T attained (FCQA, 1994).

Degree of Rotting	Range of maximum temperature value (ºC)
I	60-70
II	50-60
III	40-50
IV	30-40
V	20-30

4.1.9 Data treatment

Mean values, 95% confidence intervals and standard deviations (SD) were calculated for the data on T, MC, [O_2], BD, FAS and VS content, for each parameter, zone and plant.

4.2 Modelling analysis

All the calculations and simulations were made in Microsoft® Office Excel 2003.

4.2.1 Model fitting

The VS (volatile solids) content data (section 5.1, appendix A) was used to calculate the percentage of VS consumed in the system, in a constant ash basis, using the following expression (Schulze, 1962; Haug, 1993):

$$VS\ consumed\ (\%) = \frac{[VS_i] - [VS_f]}{(100 - [VS_f]) \times [VS_i]} \times 10^4 \quad (4.2)$$

where

$[VS_i]$ – initial concentration of volatile solids, in %

$[VS_f]$ – final concentration of volatile solids, in %

Information on the percentage of VS consumed against time was then available for each of the plants studied.

The model presented in section 2.2.7 was used to obtain calculated values of VS consumed for each process time for which experimental volatile solids values existed, in each plant. Residuals (errors) between model predictions and experimental VS consumption values were calculated for each process time point. Model estimates, namely k and $[VS_i]$ (initial volatile solids contents), were then calculated after minimizing the sum of squares of these residuals, which was done by using the "Solver" tool from Microsoft Excel 2003. Other model estimates, namely $[BVS_o]$ (initial biodegradable volatile solids content), were estimated in some situations, to be indicated in the text.

The first-order rate constants k obtained this way are corrected for the effects of T, MC, $[O_2]$ and FAS. Therefore, to a certain extent, they are independent from the operating conditions, namely regarding the environmental factors in consideration.

4.2.2 Quality of the fits and model estimates

The quality of the model fits to the experimental data was evaluated by the two following criteria (Harris, 1998; Motulsky & Christopoulos, 2003):

- Value of R^2;
- Standard error of the estimates.

The R^2 of the fit was calculated by means of the "Solverstat" tool for Microsoft Excel (Comuzzi *et al.*, 2003) and the standard error of the estimates was calculated using the

jackknife procedure (Harris, 1998). The general picture of the fit and the presence of runs of consecutive residuals of the same sign (either positive or negative) were visually evaluated.

4.2.3 Identification of outliers

In the fitting operations, the presence of outliers was detected by the use of the three standard deviations criterion, which was applied as follows. The model was fitted to the experimental data by using the procedure described above, but without the potential outlier point. A fitted curve was hence obtained, and the vertical distances (residuals) in between the experimental VS consumption points and the curve were calculated. The mean and the standard deviation of the residuals were computed, as well as the interval mean ± three standard deviations. The vertical distance of the potential outlier point to the fitted curve was then calculated, and the point actually considered as an outlier if this distance was out of the interval mentioned above.

4.2.4 Analysis of sensitivity

A simple analysis of sensitivity was performed by varying the fixed parameters of the model, one at a time, followed by the determination of the resulting change in the estimated value of k. The variation intervals for the parameters were chosen by attempting to define a likely range for each of those parameters to fall within.

The sensitivity ratio is defined as the ratio between the percentage variation of k, $\%\Delta(k)$, and the percentage variation of a parameter, $\%\Delta(\text{parameter})$, i.e.,

$$\text{Sensitivity ratio} = \frac{\%\Delta(k)}{\%\Delta(\text{parameter})} \tag{4.3}$$

4.2.5 Correction factors

Experimental data on T, MC, $[O_2]$ and FAS presented in section 5.1 and appendix A was used to calculate the corresponding correction (or limitation) factors F(T), F(MC), $F(O_2)$ and F(FAS), which are described by equation 2.29. An average value for each factor was calculated for each plant and process time. This way, information on the variation of each correction factors *versus* time was obtained for each of the four plants studied. It should be noted that, for each plant, the VS, T, MC, $[O_2]$ and FAS measurements were all made at the same process times. The exception was MBT4, where one zone was missed for MC, BD and FAS (figure 5.4). In this case, the correction factor values for the missed zones were estimated as the mean between the values corresponding to the zones before and after the missed one.

F(TOT) represents the sum of all these limiting factors, and is defined as their product (equation 2.11).

4.2.6 Estimation of k from data in the literature

k estimates obtained in this work were compared with k estimates from data available in the literature. The original data was either used directly, when available in a numerical form, or digitized with the software Engauge Digitizer, version 4.1, when only available in the graphical form.

In a few situations, the k values estimated by the authors were used. These estimates were uncorrected for the environmental conditions, namely T, $[O_2]$, MC and FAS, so they had to be corrected for these factors before they could be used for comparison, which was done using the model described in section 2.2.7. In these situations, R^2 for the model fit is not presented.

For most of the situations, k values were estimated from the original data obtained from the literature using the model adopted in this work and the procedure described in sections 4.2.1 and 4.2.6. Regarding $[BVS_0]$, it was either assumed to be 0.62 (relative to the total VS content; selected as explained in section 2.2.6), or estimated from the experimental data; these situations will be indicated in the text.

5. RESULTS AND DISCUSSION

5.1 Experimental data

The second action of this work was to develop and implement an expeditious procedure for collection of experimental data from the MBT plants under study, in order to feed the simulation model. The collected data is presented in this section.

Process time is represented in this section by the factor "zone", which has a physical significance in the composting parks of the four plants. Measurements were made, or material was sampled, in each of the several zones of the composting parks. These zones can be related to process time, where the higher the zone number, the longer the process time. These correspondences will be made in section 5.2.1 for the four MBT plants under study.

The total number of measurements made in each MBT plant is presented in table 5.1, for each parameter.

Table 5.1. Total number of measurements made for data collection on T, MC, [O_2], BD and VS content in the four plants studied.

Parameter	MBT1	MBT2	MBT3	MBT4
T	1104	154	200	429
MC	100	41	100	78
[O_2]	539	144	60	163
BD	50	21	49	21
VS content	100	41	100	78

Data on T, MC, [O_2], BD, FAS and VS contents is presented in figures 5.1, 5.2, 5.3 and 5.4 for MBT1, MBT2, MBT3 and MBT4, respectively. The original data is also presented in appendix A (tables A.1 – A.24).

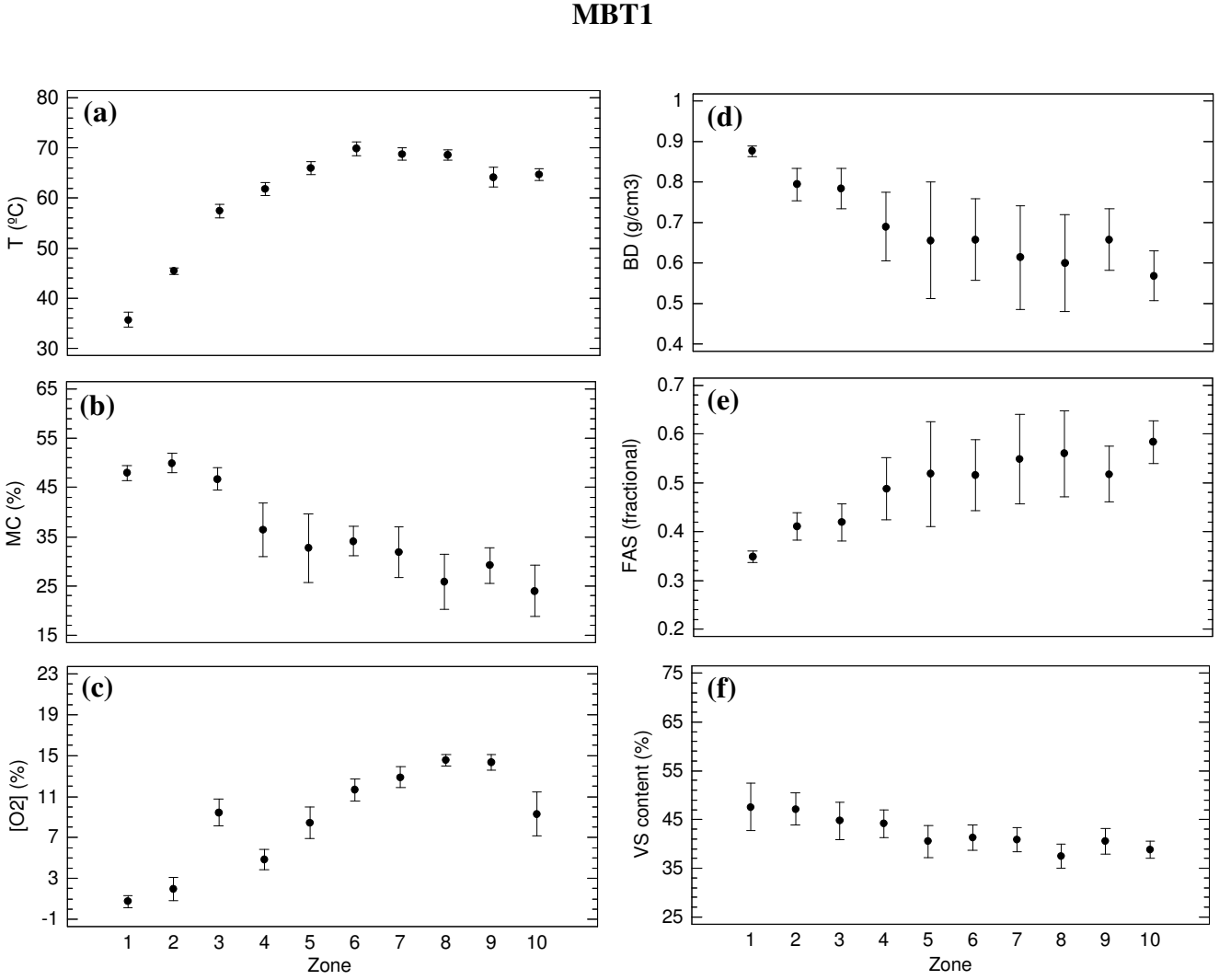

Figure 5.1. MBT1: Temperature (a), moisture content (b), oxygen concentration (c), total bulk density (d), free air space (e) and volatile solids content (f) profiles in the composting park. Mean values and correspondent 95.0 % confidence intervals.

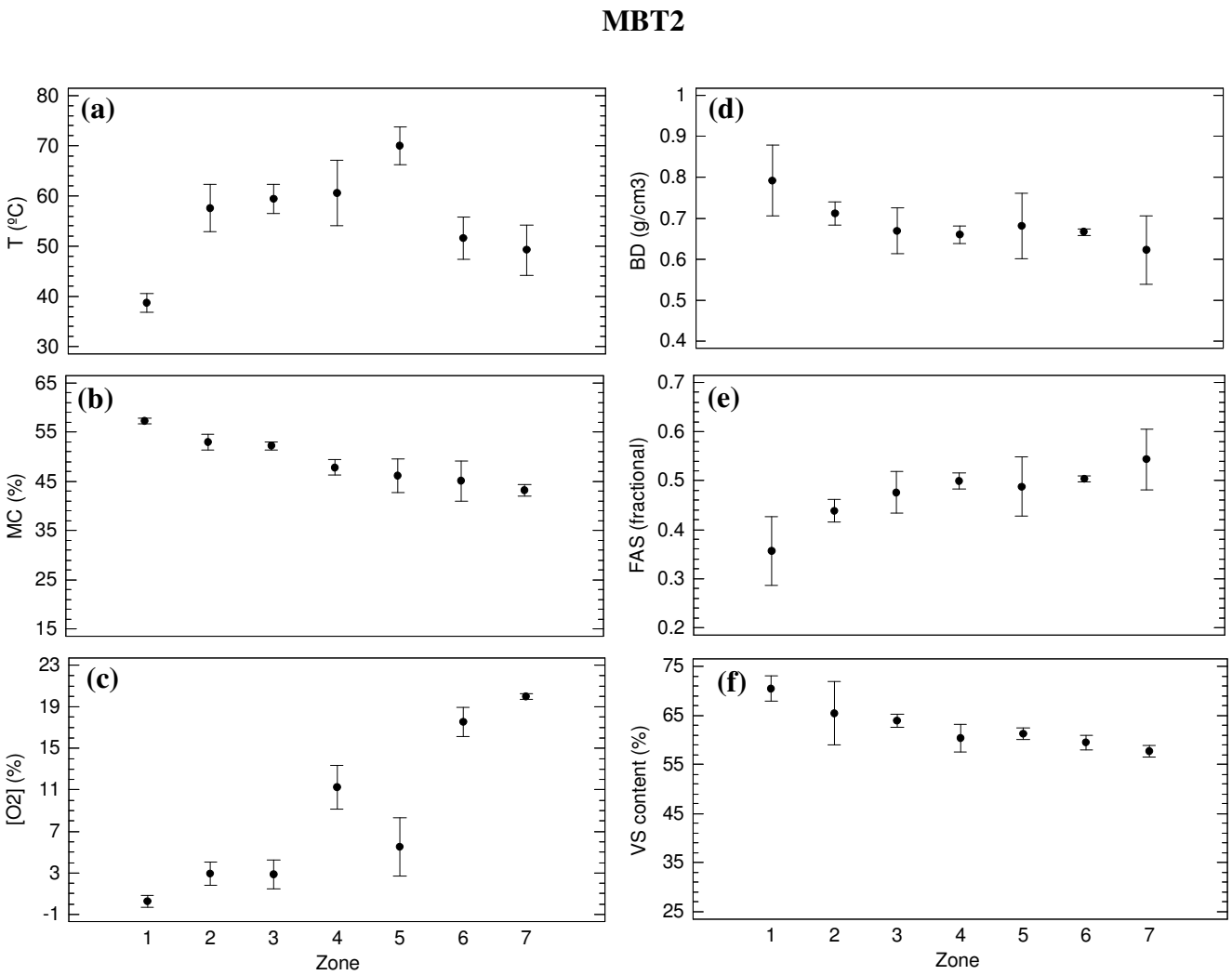

Figure 5.2. MBT2: Temperature (a), moisture content (b), oxygen concentration (c), total bulk density (d), free air space (e) and volatile solids content (f) profiles in the composting park. Mean values and correspondent 95.0 % confidence intervals.

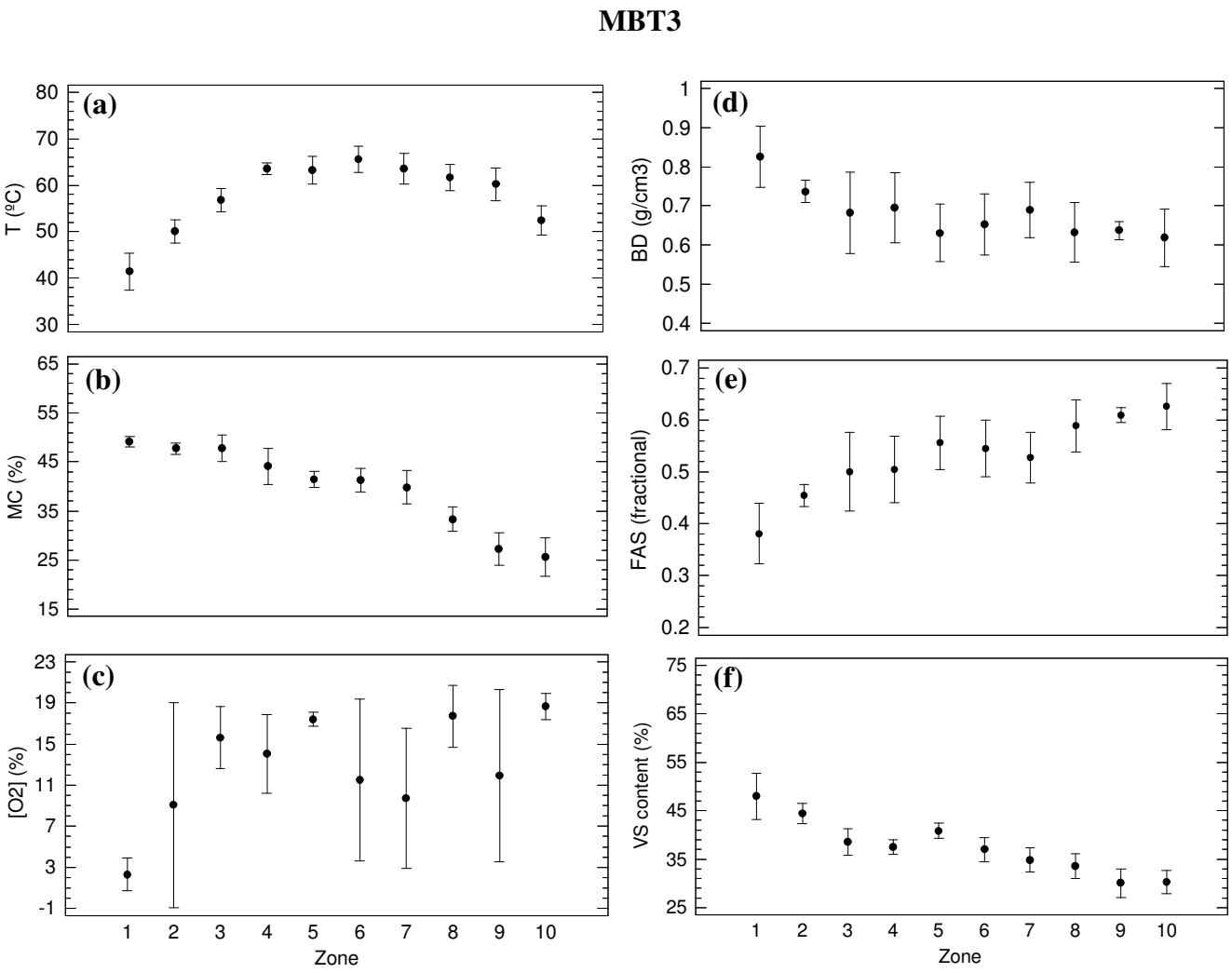

Figure 5.3. MBT3: Temperature (a), moisture content (b), oxygen concentration (c), total bulk density (d), free air space (e) and volatile solids content (f) profiles in the composting park. Mean values and correspondent 95.0 % confidence intervals.

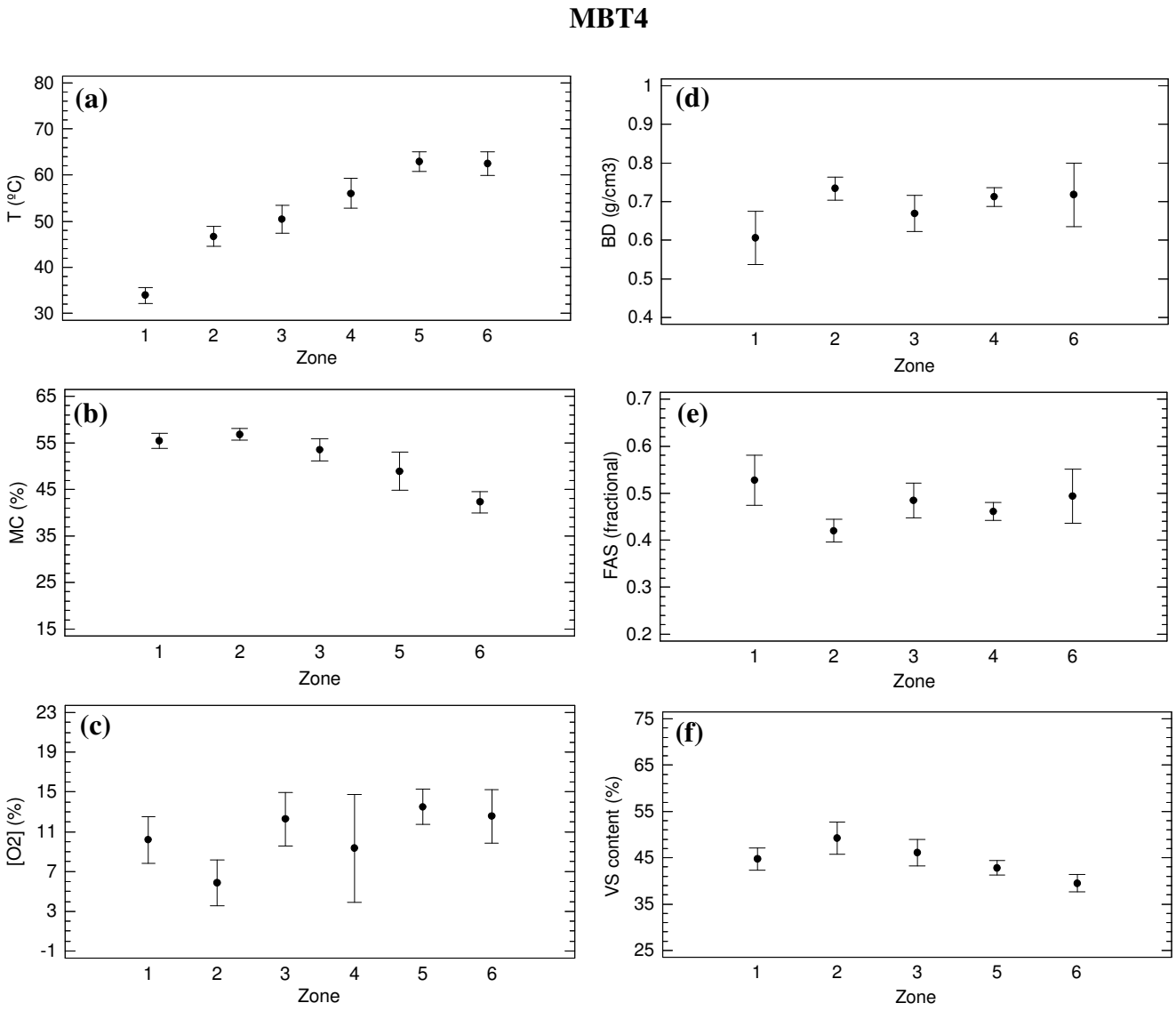

Figure 5.4. MBT4: Temperature (a), moisture content (b), oxygen concentration (c), total bulk density (d), free air space (e) and volatile solids content (f) profiles in the composting park. Mean values and correspondent 95.0 % confidence intervals.

In MBT1, the T results (figure 5.1(a)) show very small confidence intervals at 95%, which reflects the large effort made in data collection for this process parameter in this plant.

Regarding MC, the confidence intervals at 95% seem to increase along process time in the four MBT plants, which is attributed to a corresponding rise in the heterogeneities in this parameter. Differential T conditions, as well as variations in aeration performance along the same process zones, may be responsible for creating MC gradients. This, in turn, may lead to BD and FAS gradients, also denoted by the increase in the corresponding 95% confidence intervals along process time in MBT1 results. BD and FAS are strongly dependent on MC.

Concerning the VS content profiles, the 95% confidence intervals tend to decrease along process time. This trend is most evident in MBT1, but also noted in MBT2 and MBT4 results. Even though an increase in the heterogeneity in the MC and FAS conditions along the process

was noted, at least for MBT1, the turning operations which are performed along the process should tend make the material more homogeneous in terms of organic matter degradation. In addition, the reduction in particle size which occurs along the process makes the sampling operations easier and more reliable. Both these factors should contribute to an increase in the precision of the VS analysis with process time.

Another note goes for the [O_2] profile in MBT3 (figure 5.3(c)), where very large 95% confidence intervals were observed. These should result, at least in part, from the smaller effort in data collection for this parameter (table 5.1). However, an asymmetry in the ventilation system was noticed, with some tendency to have lower oxygen concentration values in the South side of some zones (Baptista *et al.*, 2003).

A more complete analysis of the data presented in this section for T, MC, [O_2], BD, FAS and VS content will be made later (sections 5.2.3.1, 5.2.3.2 and 5.2.3.3), with the aid of the simulation model.

The output composted material was subject to one further analysis, the self-heating test (figure 5.5, table 5.2).

The results of the self-heating test give an idea about the stabilization degree on the compost, revealing that none of the composts from the MBT plants under study was sufficiently stabilized: MBT1, MBT2 and MBT3 composts were classified as Rottergrad degree I, whereas MBT4 compost was out of scale. Of the four composts, the most stabilized was the one from MBT3, which is not far from class II. This is, however, not enough, as the compost should at least have a degree of rotting IV (cf. table 4.6) if it is to be considered as well stabilized, according to the Portuguese proposal for the regulation of compost (Gonçalves & Baptista, 2000). Finally, it should be referred that these test results consist of a good control to the extent of organic matter consumption, as obtained from the VS data (section 5.2.3.3).

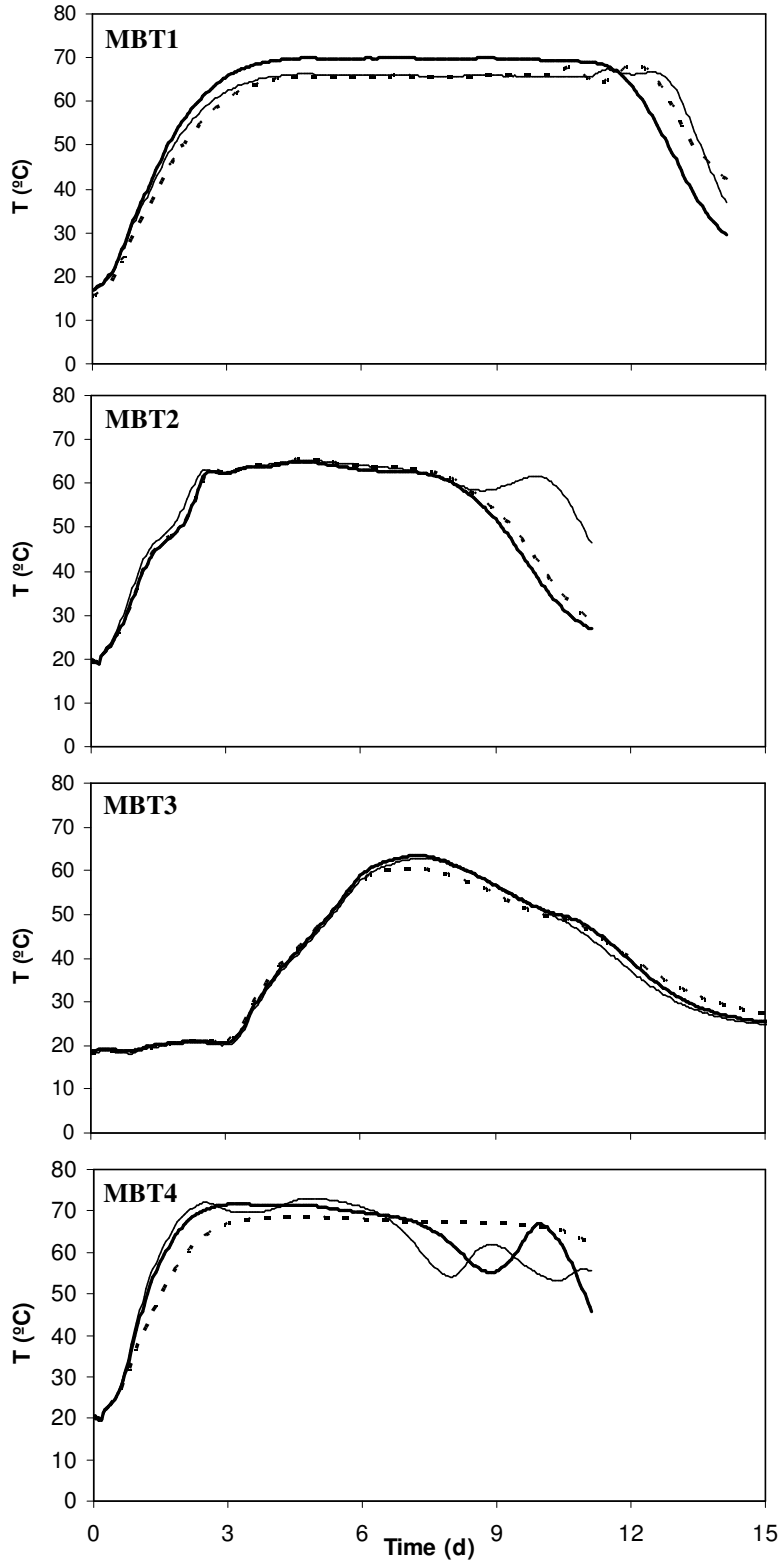

Figure 5.5. Graphical results of the temperature variation in the self-heating test. The compost from each plant was analysed in triplicate.

Table 5.2. Summary of the self-heating test results.

Parameter	MBT1	MBT2	MBT3	MBT4
Maximum temperature (ºC)*	68.5	65.3	62.2	71.1
SD	1.4	0.3	1.5	2.4
Degree of Rotting	I	I	I	-**

*Mean value of the triplicates.
**Out of scale.

In general, experimental data is considered satisfactory, especially if one takes into account that the systems under study are very large and highly heterogenic, both in terms of environmental conditions and waste composition. Full-scale composting systems are known to be difficult to study, because they are hard to control and representative measurements are difficult to obtain (Hogan *et al.*, 1989; Petiot & de Guardia, 2004; Mason & Milke, 2005a). In addition, MSW heterogeneity makes this a very difficult material to work with (Lasaridi & Stentiford, 1996; Wavrer, 1997; Scaglia & Adani, 2008; Barrena *et al.*, 2009). Therefore, a significant experimental effort had to be made for data collection. Nevertheless, contradictions can be found in the VS data, because occasional increases along process time can be observed (figures 5.1 – 5.4(f)). These are most likely due to sampling errors, and indicate that more effort should have been put in the collection of VS content data.

The procedure for data collection has the particularity of being simple to implement in practice, because the methods involved are not difficult to execute and do not require complex or too expensive equipment. In some situations, at least part of the necessary equipment is commonly used in the plants. Furthermore, data collection can be carried out by the staff working in the plant, if proper training and monitoring are provided. Therefore, these procedures can be implemented by the plant operators, which was initially a matter of concern.

5.2 Modelling analysis

5.2.1 Model fits and estimates from the experimental data

The third action of this work was to test the adequacy of the simulation model to describe the experimental data collected, and estimate k (corrected first-order reaction rate constant) for the MBT plants under study. In order to fulfil this action, the model was fitted to the experimental data collected, and the quality of the fits and estimates evaluated. The corresponding results are presented in this section.

The presentation form of the data in section 5.1, where the x-axis corresponded to the composting park zones in each plant, was converted here to process time, according to table 5.3.

Table 5.3. Correspondence of composting park zones in each plant to process time.

MBT1		MBT2		MBT3		MBT4	
Zone	Time (d)	Zone	Time (d)	Zone	Time (d)	Zone	Time (d)
1	3.2	1	3.5	1	3.6	1	1.0
2	9.4	2	10.5	2	10.1	2	3.0
3	15.8	3	17.5	3	16.7	3	5.0
4	22.0	4	24.5	4	23.2	4	7.0
5	28.4	5	31.5	5	29.8	5	9.0
6	34.6	6	38.5	6	36.3	6	11.0
7	41.0	7	45.5	7	42.8		
8	47.2			8	49.4		
9	53.6			9	55.9		
10	59.8			10	61.5		

The fitting curves and the experimental VS consumption points are presented in figure 5.6, while table 5.4 summarizes the data gathered from that figure.

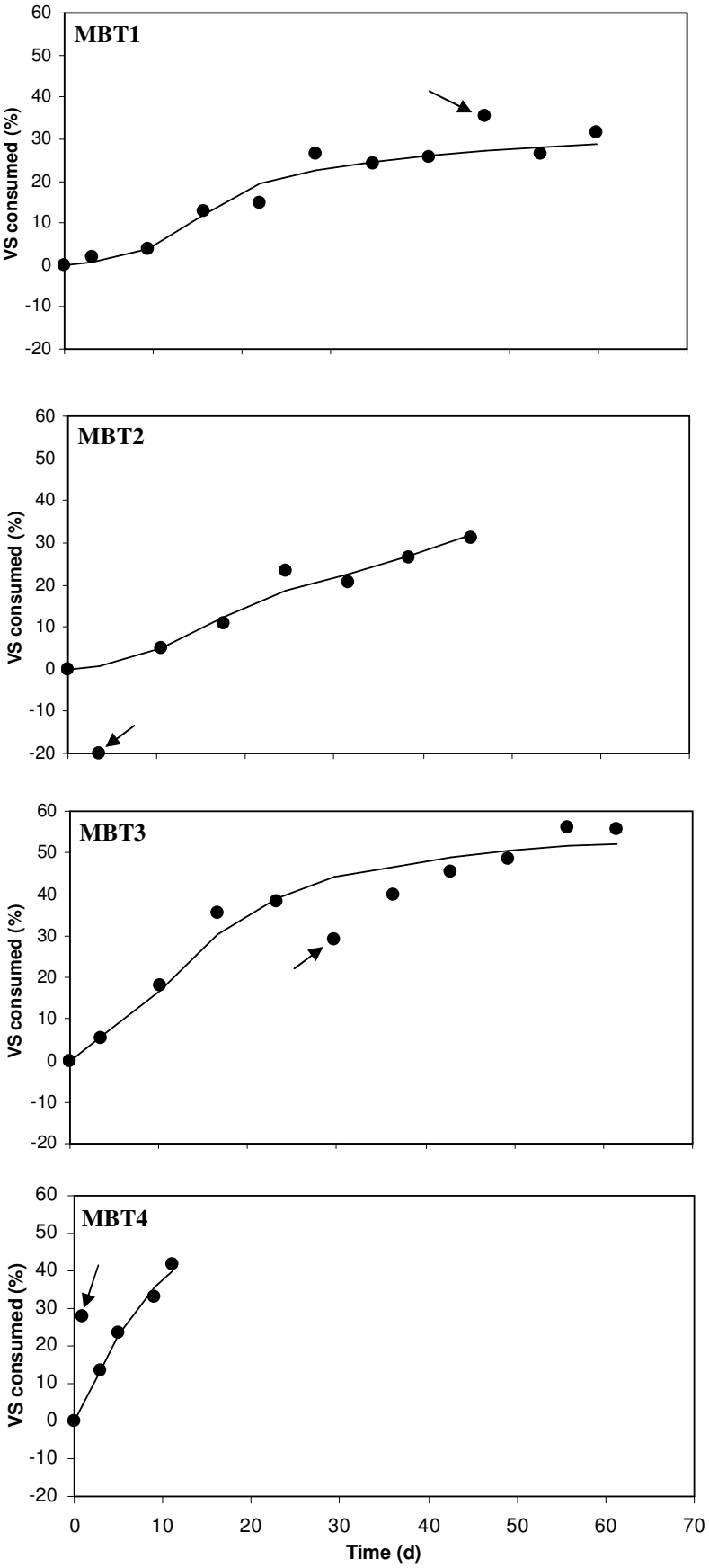

Figure 5.6. Fitting of the composting model (—) to the experimental VS consumption data (•) in the MBT plants studied in this work. Outliers identified by the three standard deviations criterion are signalled by arrows.

Table 5.4. Estimated parameters (k and VS_i) and respective standard errors, and the R^2 values for each of the plants studied.

Parameter	MBT1	MBT2	MBT3	MBT4
k ± standard error (d^{-1})	0.063 ± 0.005	0.043 ± 0.002	0.082 ± 0.011	0.22 ± 0.04
VS_i ± standard error (%)	48.1 ± 0.3	66.5 ± 0.2	48.4 ± 0.7	52.8 ± 0.8
R^2	0.958	0.965	0.964	0.991

The R^2 values in table 5.4 are acceptable in all plants, especially in the case of MBT4.

Regarding the VS_i estimates, these are similar for MBT1, MBT3 and MBT4, but higher for MBT2. This is, anyhow, not surprising, due to the different plant configuration of MBT2, in relation to the other three plants, namely in the MSW pre-treatment stage, prior to the composting process (see section 3). In MBT1, MBT3 and MBT4, pre-treatment is equivalent, but in MBT2 the presence of the rotary drums causes a significant particle size reduction in the waste. Consequently, much of the paper and cardboard in MSW is broken down to small pieces in the rotary drum, and it will be present in the fraction below 25 mm, which raises the volatile solids content in this fraction (Morvan *et al.*, 2003).

Concerning the k estimates, the values of MBT1, MBT2 and MBT3 are relatively close, but the one for MBT4 it is quite higher (table 5.4, figure 5.7).

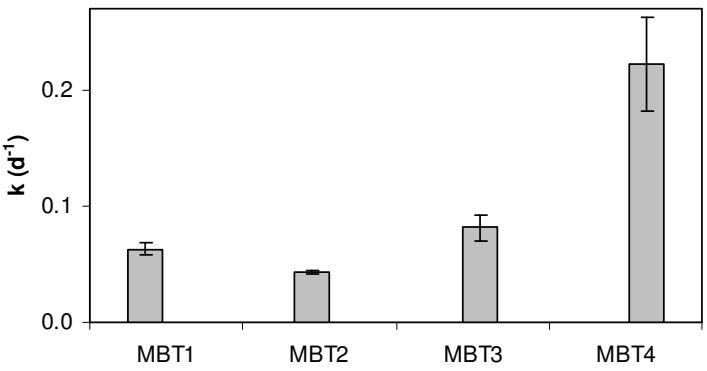

Figure 5.7. Estimated k values for the four plants in this study. Error bars correspond to the standard errors.

MBT1 and MBT3 are very similar in terms of configuration (section 3) and in terms of the waste fraction for composting, judging from the estimated VS_i contents (table 5.4). The fact that the estimated k values are similar in these two plants is therefore an indicator in favour of the experimental procedure for data acquisition and the simulation model used here. This is specially so because, as will be concluded from section 5.2.3, operation performance in MBT3 is much better than in MBT1.

Regarding MBT2, the k estimate is lower than the ones from MBT1 and MBT3. This is not totally unexpected, as the higher paper content of the composting waste in MBT2 is likely to cause a decrease in the k value (c.f. table 6.1). However, there is also a factor in MBT2 that

may contribute to an increase in k, which is the smaller particle size of the composting waste, already mentioned above. Unfortunately, waste composition and particle size could not be considered in the simulation analysis, and it is probably a balance between these two factors that results in a k value that seems to be slightly smaller than the ones from MBT1 and MBT3.

Nonetheless, the k estimates for MBT1, MBT2 and MBT3 are within the same range, whereas k for MBT4 is quite apart from the others. One possible explanation for such a high k value is related to the short process time in MBT4, 12 days, in relation to the others, i.e., approximately 63, 49 and 60 days for MBT1, MBT2 and MBT3, respectively. The composting process is normally modelled using a one-time scale exponential model, but, in some situations, a two-time scale exponential model has proven to perform better (Haug, 1993; Kim *et* al, 2000; Ndegwa *et* al, 2000; Cronjé *et* al, 2004; Zavala *et al.*, 2004a, 2004b; Komilis, 2006; de Guardia *et al.*, 2008; Mason, 2008a, 2009; Tosun *et al.*, 2008). In the two-time scale version, the substrate is considered to be composed of two fractions: a fast fraction, which is degraded at a fast rate, and which dominates the kinetics in the early stages of the composting process; and a slow fraction, which is consumed at a slower rate, and which governs the kinetics in the late process stages. In MBT4, as process time was restricted to a period of 12 days, the kinetics were likely to be dominated by the fast, more easily biodegradable fraction, which can explain the higher k value obtained.

Anyway, a VS consumption of around 40% in 11 days (figure 5.6) is excessively high and unexpected, even though a high material turning frequency is practiced (once every two days). In addition, this result is not in accordance with the results for the self-heating test (table 5.2), as these reveal that the composted material from this plant is very badly stabilized, being the worst in the set of four.

Another possible explanation which results in a more realistic VS degradation performance (around 20% in 11 days) is related to sampling errors, especially in the first stages of the process. Even though large sample sizes were used for the VS determinations (section 4.1.4), the high heterogeneity of the composting material makes this a difficult material to work with, which is apparent in the VS data in figure 5.4(f). The data point corresponding to zone 1 (1 day average process time) was rejected in this analysis, but rejection of the data point corresponding to zone 2 (3 days average process time) would also make some sense. Actually, the three standard deviations criterion does not exclude this data point, but if two standard deviations were used instead, this point would be rejected. In this scenario (rejecting the data point of 3 days and maintaining the 1 day data point), the graph in figure 5.8 would be obtained. The model fitting is not as good as when the 1 day data point is rejected (please see

figure 5.6), but this is a possible scenario. In this case, the estimated k is 0.082 ± 0.13 d^{-1}, which is well within the range of the k values obtained for the other plants (table 5.4). However, the standard error increases, and R^2 decreases (0.695), to unacceptable levels. The VS_i estimate decreases to 46.6%.

It should be noted that a redistribution of the experimental points around the fitted line occurs, in relation to figure 5.6. This is due to the fact that the experimental points are dependent on the VS_i value, which is estimated in the fitting procedure.

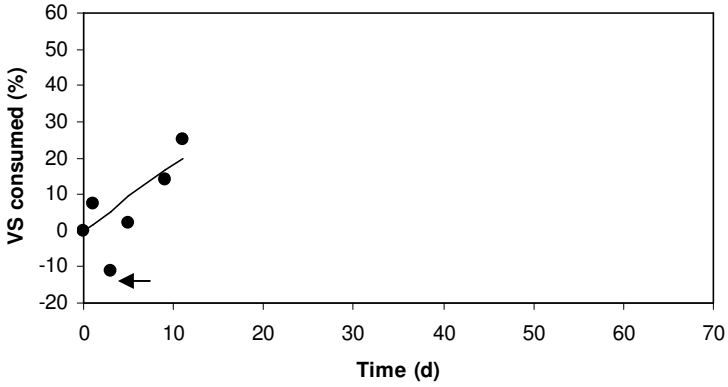

Figure 5.8. MBT4: Fitting of the composting model (—) to experimental VS consumption data (•) when the data point correspondent to 1 day is maintained and the one correspondent to 3 days (signalled by an arrow) is rejected.

In any case, the k estimate obtained for MBT4 will not be used for the purpose of comparison with kinetics data obtained from the literature (section 5.3), since there is too much uncertainty around this value.

Lastly, it should be mentioned that fitting of the experimental data obtained here to a two-time scale exponential model was attempted (results not shown), but for this model each data set had several solutions. It is suspected that the experimental data does not have enough information to support such a model, due to the scattering in the data. This does not mean, however, that the composting process is not better described by a two-time scale exponential model than it is by a one-time scale exponential model.

5.2.2 Analysis of sensitivity

k estimation from the experimental data (section 5.2.1), with the model and the procedure presented in sections 2.2.7 and 4.2.1, respectively, is affected by the values assumed for the several parameters in the model. Of these parameters, some are known with more certainty than others. It is, therefore, important to be aware of which of these parameters are the most influential in k estimation, and how much a variation in one parameter affects the k estimate. This constituted the fourth action of this work, which was achieved by means of a simple sensitivity analysis, summarised in table 5.5.

Table 5.5. List of parameters and actions involved in the analysis of sensitivity, and respective description.

Parameter	Action	Reference value	New value
$[BVS_o]$	Increase 10%	62%	68.2%
$[BVS_o]$	Decrease 10%	62%	55.8%
T_{min}	Increase 100%	5ºC	10ºC
T_{min}	Increase 300%	5ºC	20ºC
T_{min}	Decrease 100%	5ºC	0ºC
T_{max}	Increase 12%	71.6ºC	80ºC
T_{max}	Decrease 5%	71.6ºC	68ºC
T_{opt}	Increase 10%	58.6ºC	64.46ºC
T_{opt}	Decrease 10%	58.6ºC	52.74ºC
K_{O_2}	Increase 10%	0.83% (v/v)	0.913% (v/v)
K_{O_2}	Decrease 10%	0.83% (v/v)	0.747% (v/v)
MC_{opt}	Increase aprox. 10%	A=7.0622*	A=7.7696*
MC_{opt}	Decrease aprox. 10%	A=7.0622*	A=6.3548*
FAS_{opt}	Increase aprox. 20%	A=3.4945**	A=4.2048**
FAS_{opt}	Decrease aprox. 20%	A=3.4945**	A=2.7842**

* A in $F(MC)=\frac{1}{e^{(-17.684\times(1-DM)+A)}+1}$

** A in $F(FAS)=\frac{1}{e^{(-23.675\times FAS+A)}+1}$

The results of this analysis (figures 5.9 and 5.10 and table 5.6) show that:

- The behaviour of the four plants studied is relatively similar, concerning the response of k to the set of actions studied in the sensitivity analysis;
- The sensitivity ratios for T_{min}, K_{O_2} and FAS_{opt} are very low, which means that these parameters have a very small influence in the estimation of k;

- The most influential parameters (which cause the sensitivity ratios to be higher) are [BVS_o], Tmax and MC_{opt} (and the composting rate dependence on MC);
- The magnitude of the variation of k caused by a variation in the model parameters was quantified (according to section 4.2.4). In this respect, it is worth noting that sensitivity ratios between 3 and 4 are not uncommon, which means that a certain percentage variation in the model parameter is amplified by 3 to 4 times in the k estimate.

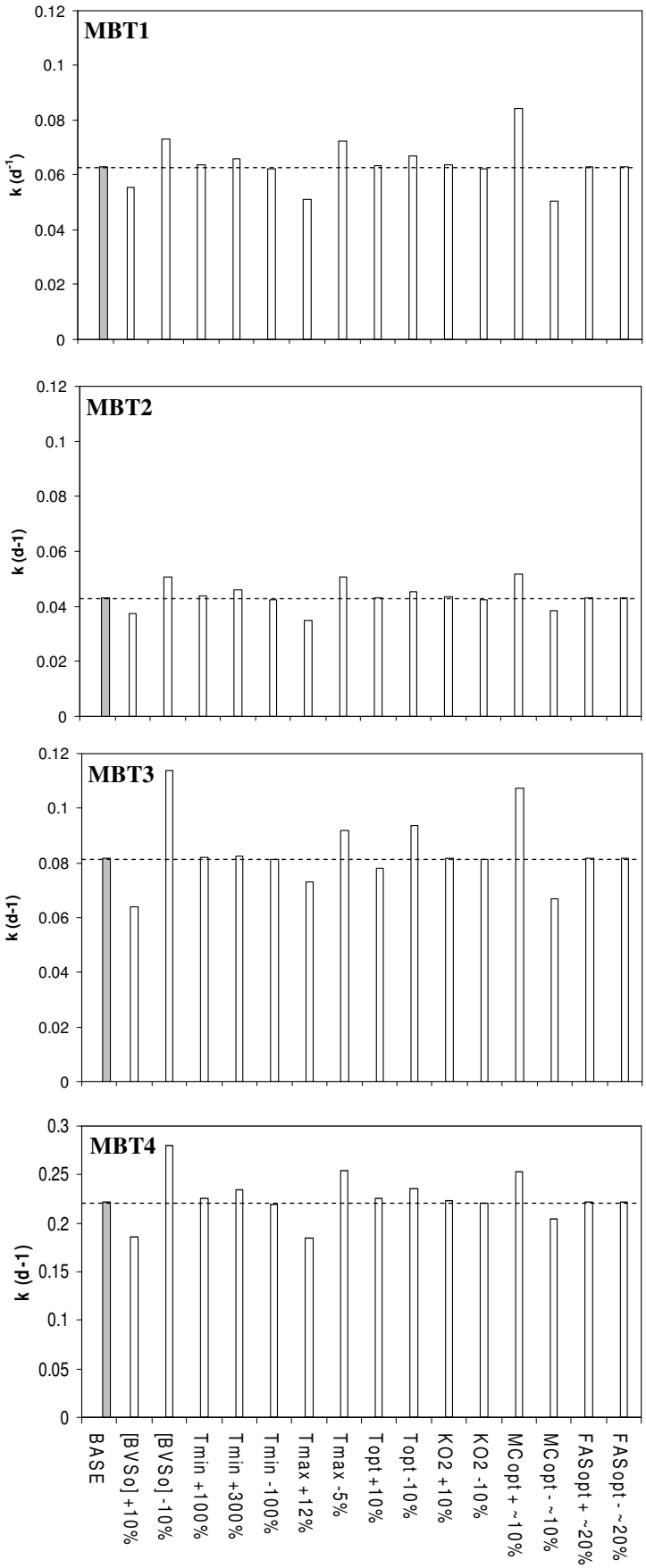

Figure 5.9. Sensitivity analysis - k values obtained for each action. Base represents the k value estimated for the base scenario, where the parameters assume their default values, and it is the reference to which the other values shall be compared.

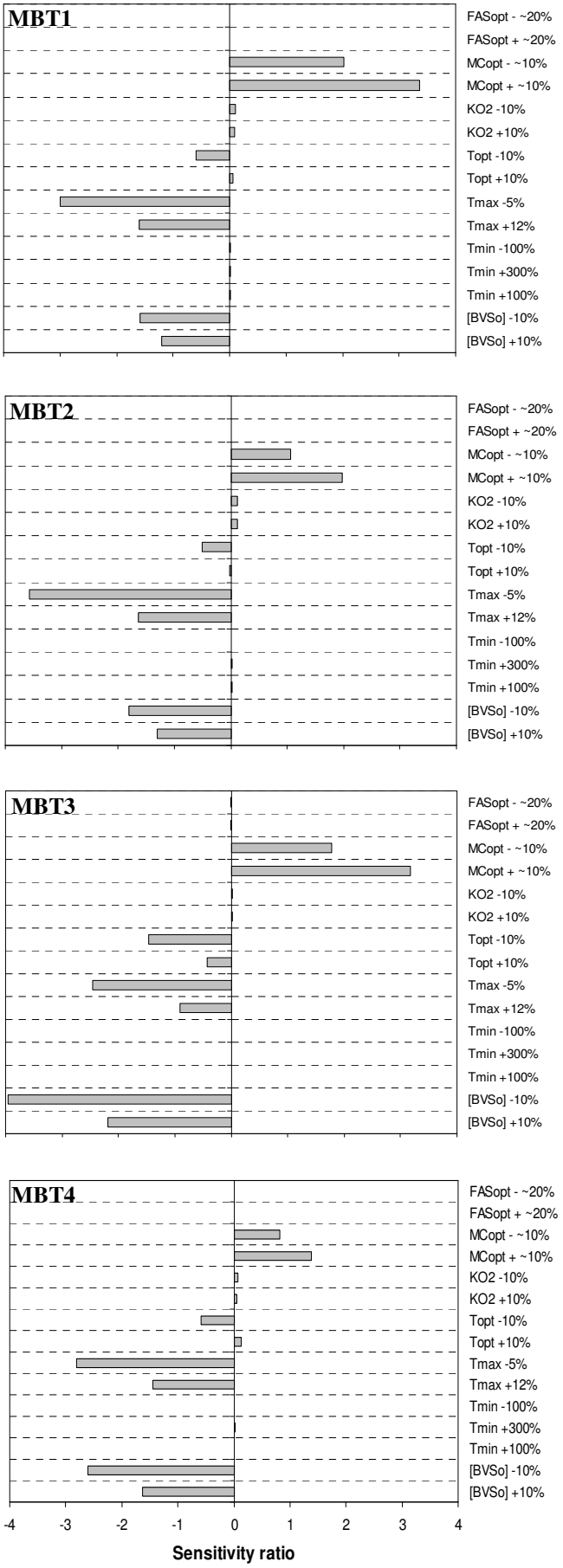

Figure 5.10. Sensitivity analysis - sensitivity ratios obtained for each action.

Table 5.6. Summary of the sensitivity ratios for the actions involved in the analysis of sensitivity. The higher sensitivity ratios are highlighted in bold.

Action	Sensitivity ratio				
	MBT1	MBT2	MBT3	MBT4	Average
[BVSo] +10%	**-1.2**	**-1.3**	**-2.2**	**-1.6**	**-1.6**
[BVSo] -10%	**-1.6**	**-1.8**	**-4.0**	**-2.6**	**-2.4**
Tmin +100%	0.01	0.02	0.003	0.01	0.01
Tmin +300%	0.02	0.02	0.004	0.02	0.01
Tmin -100%	0.01	0.02	0.003	0.01	0.01
Tmax +12%	**-1.6**	**-1.6**	**-0.9**	**-1.4**	**-1.4**
Tmax -5%	**-3.0**	**-3.6**	**-2.5**	**-2.8**	**-3.0**
Topt +10%	0.06	-0.02	-0.43	0.14	-0.06
Topt -10%	-0.6	-0.5	-1.5	-0.6	-0.8
K_{O_2} +10%	0.10	0.11	0.02	0.06	0.07
K_{O_2} -10%	0.10	0.12	0.03	0.06	0.08
MCopt + ~10%	**3.4**	**2.0**	**3.2**	**1.4**	**2.5**
MCopt - ~10%	**2.0**	**1.1**	**1.8**	**0.8**	**1.4**
FASopt + ~20%	0.007	0.001	-0.001	0.003	0.003
FASopt - ~20%	0.003	0.001	-0.001	0.001	0.001

Regarding the most influential parameters, the variation ranges they were submitted to in this analysis were defined taking into account the information given in section 2.2. This means that an attempt was made to define realistic variation intervals, within which the parameters are likely to lie. The corresponding intervals for the k estimates can thus be defined taking into account the limit k values obtained in this sensitivity analysis. These are presented in table 5.7. The intervals for k defined in this way are always larger than the corresponding standard errors, as obtained by the jackknife procedure (section 4.2.2).

Table 5.7. k range as obtained from: (i) the k estimates and standard errors from section 5.2.1, and (ii) the variation of k in response to the actions carried out in the sensitivity analysis.

Plant	k range (d^{-1}) from section 5.2.1	k range (d^{-1}) from the sensitivity analysis
MBT1	0.058 – 0.068	0.050 - 0.084
MBT 2	0.041 – 0.045	0.035 - 0.052
MBT 3	0.071 – 0.093	0.064 - 0.114
MBT 4	0.18 – 0.26	0.18 - 0.28

5.2.3 Diagnosis of the composting plants

Diagnosis of the conditions at which the MBT plants under study are operating, at the level of the composting process, constituted the fifth action of this work. In order to complete it, the first step was the monitoring of the environmental conditions (T, MC, $[O_2]$ and FAS) throughout the process. VS contents were also measured and used as the process monitoring parameter. Then, this information, which was presented in section 5.1 and in appendix A, was transformed here in such a way that facilitates the diagnosis of the composting process. This transformation involved the calculation of the following:

- Correction factors F(T), F(MC), $F(O_2)$, F(FAS) and F(TOT);
- k' (uncorrected kinetic rate constant);
- VS degradation patterns.

The significance of these factors, as well as the results and information taken from them, are presented in the next sections.

5.2.3.1 Correction factors

The simulation model adopted in this work considers that the composting rate is limited by four environmental factors – T, MC, $[O_2]$ and FAS. These limitations are represented individually in the model by the factors F(T), F(MC), $F(O_2)$ and F(FAS), respectively, which are described in equation 2.29.

F(TOT) is defined as the product of the 4 correction factors (equation 2.11) and represents the sum of all the limiting factors, i.e., the total limitation to process rate. It is variable along process time, and it actually gives an idea about the overall operation performance in each plant, in terms of maintaining optimum environmental conditions for the composting process. This performance is a function of two factors: i) operators' expertise and ii) composting system performance, from the standpoint of the engineering potential of the system to fulfil optimum environmental conditions for the microbial composting population.

Therefore, the limitations by the environmental conditions at any process time are given globally by F(TOT) and individually by F(T), F(MC), $F(O_2)$ and F(FAS). Each factor can vary between 0 and 1; 1 represents no limitation by that factor, 0 represents maximum limitation, at which F(TOT) is 0, and, consequently, composting rate also equals 0.

Data on the variation of the correction factors against process time is presented in figure 5.11. Information on the most limiting factors in each plant, in the different process stages, is summarised in table 5.8.

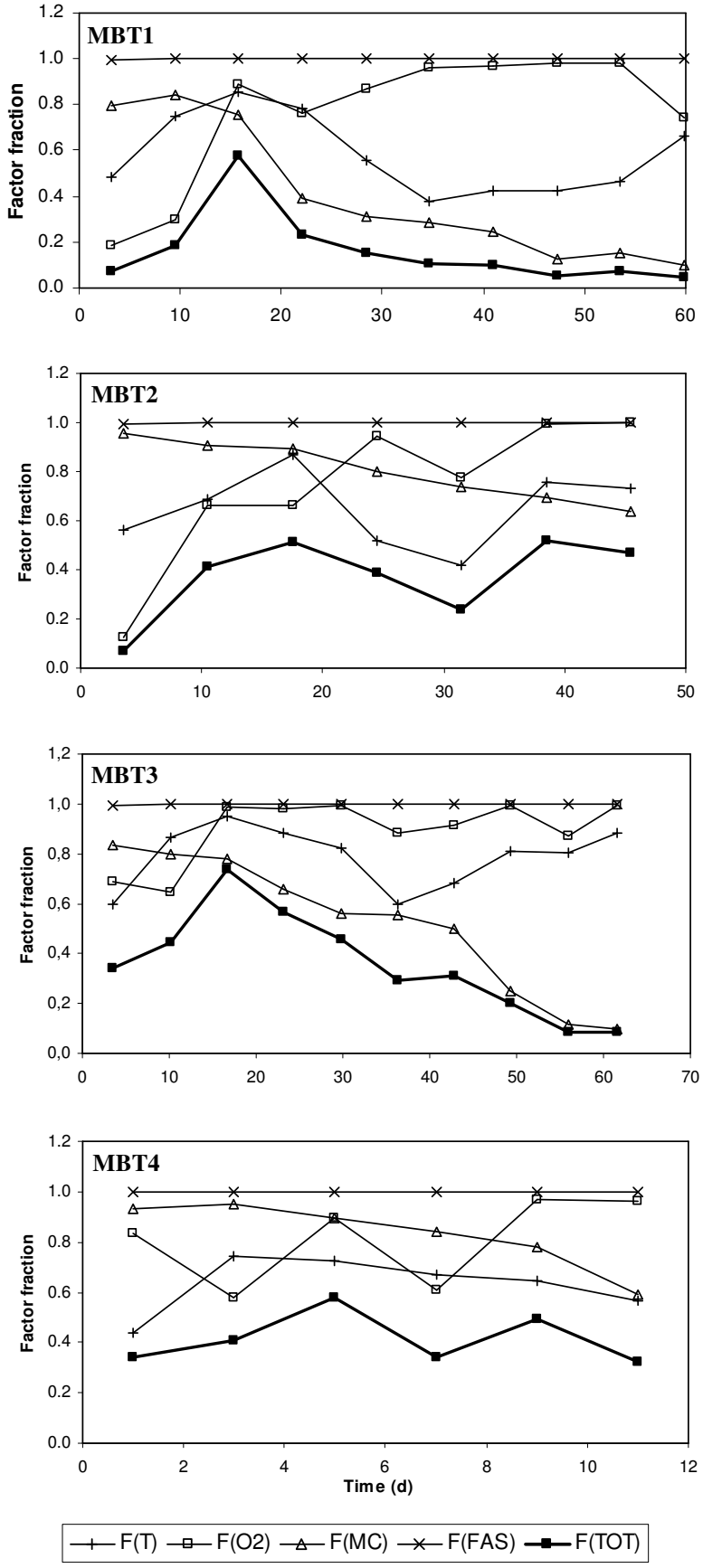

Figure 5.11. Variation of the correction factors F(T), F(MC), $F(O_2)$, F(FAS) and F(TOT) along process time in the plants studied.

Table 5.8. Most limiting factors in the initial, middle and final stages of the composting process in the plants studied.

PLANT	Initial stage	Middle stage	Final stage
MBT1	F(T), F(O_2)	F(T), F(MC)	F(MC), F(T)
MBT2	F(T), F(O_2)	F(T)	F(MC)
MBT3	F(T), F(O_2)	F(T), F(MC)	F(MC)
MBT4	F(T), F(O_2)	F(T), F(O_2)	F(MC), F(T)

One general observation is that FAS was never a limiting factor, in no plant and no process stage. This may actually be the case, as the composting material, i.e., the pre-treated MSW, has quite a high percentage of hard materials like glass, stones, wood, plastics, etc, which in the end play the role of a bulking agent. However, there is also the chance that this is not true, because FAS is a very difficult parameter to measure experimentally (Annan & White, 1998; Agnew & Leonard, 2003; Su *et al.*, 2006; Albuquerque *et al.*, 2008). One of the main problems is to reproduce in the measuring equipment the compression load to which the materials are subject to in the real-scale pile. Things are made even more difficult because compression load varies with depth in the pile (Schaub-Szabo & Leonard, 1999; Van Ginkel *et al.*, 1999; McCartney & Chen, 2000, 2001). Therefore, the measured FAS may have been higher than the average FAS in the pile, because the compression rate applied to the material in the measurements may have not been high enough to reproduce the average field conditions. In fact, the method for the determination of BD (total bulk density) used here (method 03.01-C from Thompson *et al.* (2002)), from which FAS was calculated according to section 4.1.7, although simple and fast to execute, includes a compression step that is fixed and, consequently, does not account for variables like material type or pile height.

Furthermore, the analytical procedure for FAS determination is also a factor of variability. Works by Annan & White (1998), Eftoda & McCartney (2004) and Su et al. (2006) indicate that different methodologies for FAS determination can produce very different results. In this respect, the approach used here for the FAS determination (section 4.1.7) has proven to provide accurate FAS estimates, when compared to experimental results obtained by more precise experimental methods, like the air pycnometer method (Annan & White, 1998; Richard *et al.*, 2002, 2004; Su *et al.*, 2006; Ahn *et al.*, 2008).

It should be mentioned that FAS has been measured in the laboratory with more reliable methods, which apply a load to the sampled material that is calculated according to the depth and type of the material in the pile, thereby reproducing the real conditions more accurately (McCartney & Chen, 2000, 2001; Schaub-Szabo & Leonard, 1999; Agnew *et al.*, 2003; Eftoda & McCartney, 2004; Richard *et al.*, 2004; Ahn *et al.*, 2008). Application of such

methods should lead to more accurate conclusions about the influence of FAS on the composting rate, for the materials under study.

Regarding the initial stage of the process, there was a limitation caused by excessively low T and [O_2] conditions in all plants (please refer to figures 5.1 – 5.4 to see the experimental data). The low T conditions are to be expected, as the composting material enters the process roughly at ambient T, or slightly higher, and it takes some time for the heat produced by the microorganisms' respiration activity in the process to raise the material T to more favourable levels (Gootas, 1956; Golueke, 1972, Jeris & Regan, 1973a; Haug, 1993).

In the case of [O_2], the low levels may reveal either one or both of the following:

- A deficient air supply system, which does not have the capability to maintain appropriate [O_2] levels;
- An unfavourable structure of the composting material for aeration. This would come in support of the hypothesis that FAS may have been overestimated. FAS tended to increase along the composting process in this study, except for MBT4, because of the very short process time (figures 5.1 – 5.4(e)). Anyhow, the most severe FAS limitations are generally observed in the initial stages of the process (Haug, 1993), and this may have been the case here, which can also explain the relatively low levels of [O_2] observed.

In the middle stages of the composting process, T was a significantly limiting factor in all the studied plants. This was due to excessively high process temperatures, which were not limited to the optimum range of around 58.6ºC (section 2.2.2). Process T values above 70ºC were common, with the occasional value going up to 80ºC and more (appendix A, tables A.1, A.7, A.13 and A.19). The maximum T value measured in this work was 84.9ºC.

MC was also a significantly limiting factor in the middle process stages in MBT1 and MBT3. The water produced in the composting process was not enough to compensate for the moisture losses, which are generally very significant because heat loss occurs mainly by evaporative cooling (Finstein *et al.*, 1986a, 1986b, 1987a). In the case of MBT3, where water is added throughout the process, this was also not enough to compensate for the losses.

In the case of MBT4, [O_2] was still significantly limiting process rate.

In the final stages of the process, composting rate was significantly limited by the low MC levels. Heat loss occurs mainly by evaporative cooling, as pointed out above, and this leads to high moisture losses. This MC reduction is however necessary, in order to allow for efficient mechanical post-treatment of the final compost.

T was still significantly limiting the process rate at this stage in MBT1 and MBT4, due to excessively high T (section 2.2.2). In MBT4, these high T are observed because the total

process time is too short (12 days) for a satisfactory stabilization of the composting material. In MBT1, although process time is longer (63 days), poor process management hampers the stabilization of the composting material, as observed from the low VS consumption (figure 5.6) and from the results of the self-heating test (table 5.2). Therefore, in these two plants, the incomplete stabilization of the composting material, together with a deficient air supply, are causing T to be high in the final process stages.

Regarding F(TOT), information for the plants under study was gathered in figure 5.12, for comparison purposes.

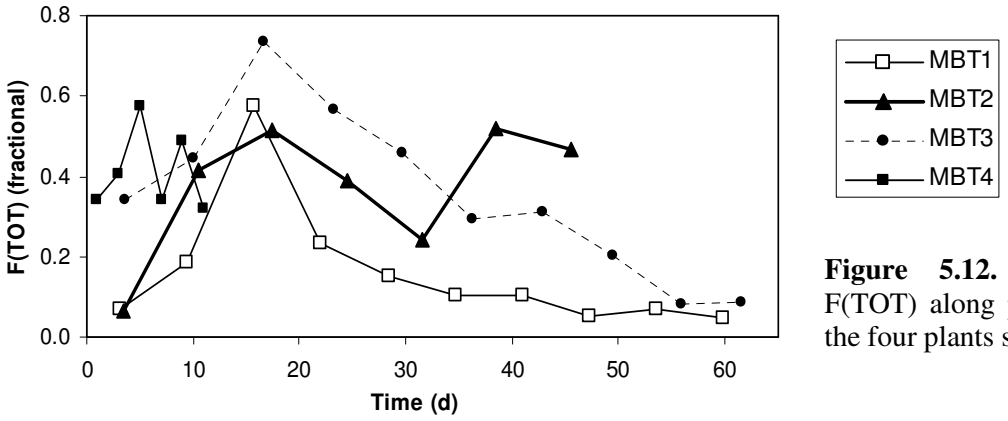

Figure 5.12. Variation of F(TOT) along process time in the four plants studied.

MBT4 is an isolated situation in this set of four plants, as process time is much shorter, and the material turning frequency is much higher (every two days) than in the other plants. This higher turning frequency is assumed to be the responsible for the better performance of this plant in terms of F(TOT), when compared to the other plants, in the same time period, due to the favourable role of the turning operations in the composting process.

Regarding MBT1 and MBT3, figure 5.12 illustrates how operation performance is important in a MBT plant. Actually, these two MBT plants have similar equipments and plant configurations (cf. section 3), and treat very similar wastes (table 5.4), but the better operation in MBT3 leads to a much smaller process limitation than in MBT1. F(TOT) was, on average, two decimal points lower in MBT1 than in MBT3. This has a strong effect in the global VS consumption, being much smaller in MBT1 than in MBT3 (figure 5.6). MBT3 F(TOT) performance was actually very close to MBT4, in the latter's time scale.

Regarding MBT2, this plant global performance, as evaluated by F(TOT), is somewhere between MBT1 and MBT3. However, in the final stage of the process, MBT2 has the best performance, which is mainly due to the fact that the operating MC level (around 43% by the end of the process) is not as low as in the other plants. Nevertheless, these more favourable MC conditions for the composting process may reduce the efficiency of the post-treatment stage (Morvan *et al.*, 2002, 2003). Such a high water content causes clogging of the refining

trommel and densimetric tables, causing the equipment efficiency to decrease and the maintenance costs to increase. Therefore, the overall efficiency of the plant is affected.

5.2.3.2 Uncorrected first order reaction rate constant

In addition to the F(TOT) analysis, it is also interesting to analyse the values of k' in the studied plants. k´ is related to k through equation 2.12. Therefore, k' gathers information about k and operation performance all in one parameter. Information about operation performance is contained in the correction factors included in the model, and has already been considered (section 5.2.3.1). k' analysis goes a step further in relation to the F(TOT) analysis, because it gathers information of F(TOT) and k. k´ tells us how the system works, indicates the actual performance of the plant as a whole, along process time. It is a function of the system performance, the type of material under treatment, the operation performance, and any other factor that may affect the overall performance.

As k is a constant, but the correction factors vary along process time, k' varies accordingly. A plot of k' *versus* process time is given in figure 5.13.

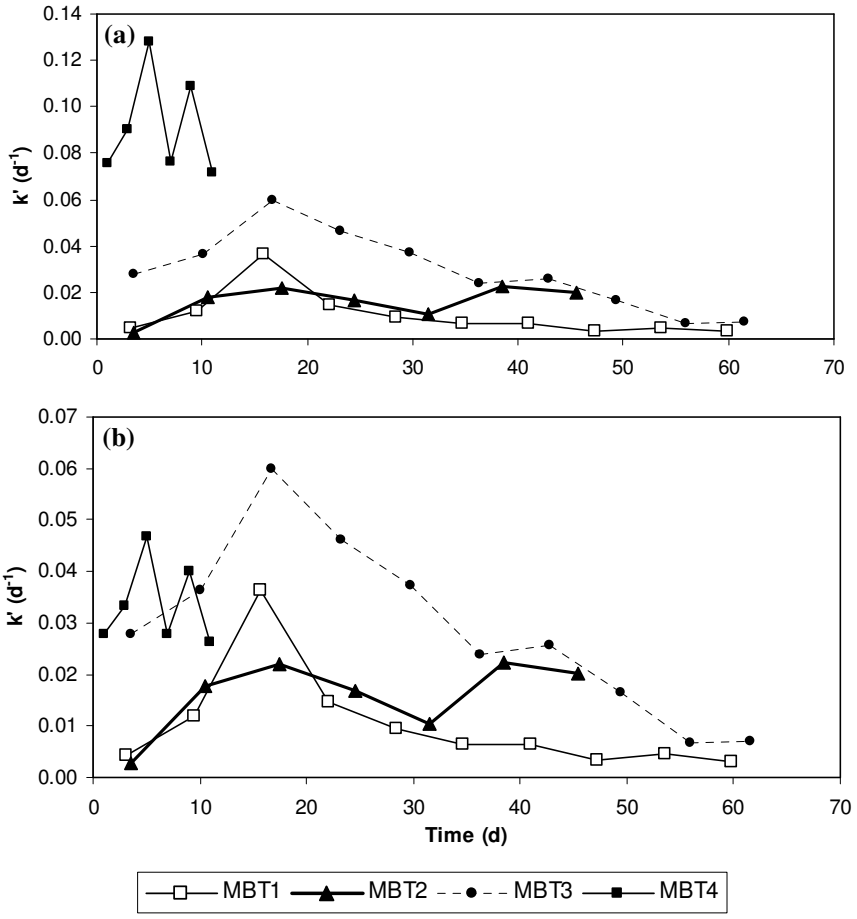

Figure 5.13. Plot of k' (apparent first-order reaction rate constant) along process time, for the studied plants. k used for MBT4 was: (a) 0.22 d^{-1}; (b) 0.082 d^{-1} (please refer to section 5.2.1).

From figure 5.13(a) one observes that the k' of MBT4 is isolated from the k' of the other plants. This is mostly due to the much higher k value obtained for this plant, in relation to the others. However, if, as discussed in section 5.2.1, a k of 0.082 d^{-1} is considered instead of 0.22

d^{-1}, than the situation changes significantly (figure 5.13(b)). In this case, k' of MBT4 is still above k' for MBT1 and MBT2, but in the range of MBT3, tending to be slightly higher in its time range.

Analysis of figure 5.13 corroborates the conclusions from the F(TOT) analysis (section 5.2.3.1). All the same, it is worth mentioning the very good performance of MBT3, which is even more evident in this analysis. MBT3 performance is close to MBT4 performance, in the latter's time scale, even though the high turning frequency in MBT4 constitutes a process management advantage.

5.2.3.3 VS degradation patterns

VS content was the parameter chosen in this work for process rate evaluation. Determination of volatile solids content is made by a quick and simple method, which gives an estimate of the amount of organic matter in the sample (section 4.1.4). Along the composting process, the fact that organic matter is being degraded, leads to a decrease in the volatile solids content of the material. Therefore, when VS experimental data are transformed in VS degradation data in a constant ash basis (equation 4.2), a direct measure of process performance is obtained.

The VS consumption patterns presented in figure 5.6, corresponding to the model fits to experimental data, were gathered in one graph (figure 5.14), for comparison purposes.

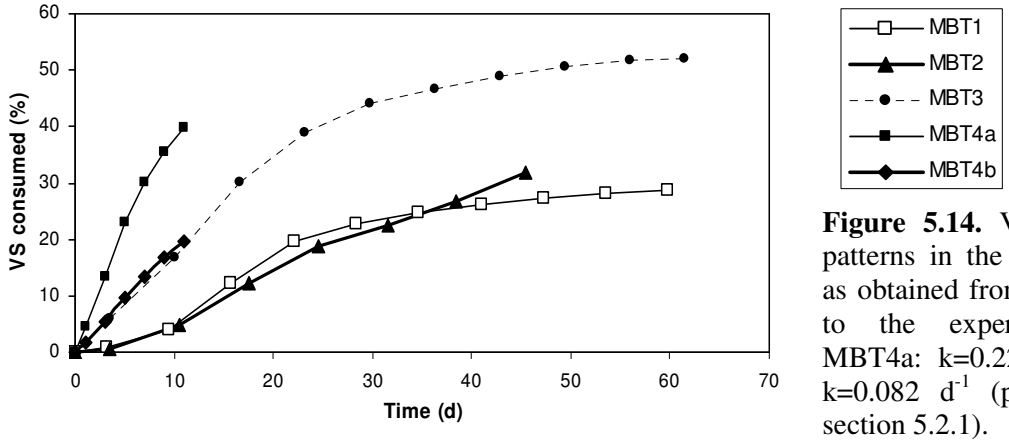

Figure 5.14. VS degradation patterns in the plants studied, as obtained from the model fit to the experimental data. MBT4a: k=0.22 d^{-1}; MBT4b: k=0.082 d^{-1} (please refer to section 5.2.1).

Data on figure 5.14 provides direct information on process performance evaluation. MBT4 was the best performing plant, with around 40% VS degradation in 11 days (MBT4a in figure 5.14). But again, if, as discussed in section 5.2.1, a k of 0.082 d^{-1} is considered instead of 0.22 d^{-1}, than the VS degradation pattern changes considerably (MBT4b in figure 5.14). In this case, VS degradation in MBT4 is around 20% in 11 days, and process rate is very close to the one in MBT3. This result is more in accordance with the results from the self-heating test (table 5.2), which indicate that the compost from MBT4 is very poorly stabilized, the worst in the four plants studied.

MBT3 was the plant where the greatest final VS consumption was observed, namely 52% in 61.5 days.

MBT1 and MBT2 were the plants with the worst performance, MBT2 performing slightly better than MBT1, because a slightly higher VS consumption was achieved in a shorter process time.

Overall, the conclusions taken from the VS degradation data are in good agreement with those taken from the correction factors and k' analysis (sections 5.2.3.1 and 5.2.3.2, respectively), and with the results from the self-heating test (table 5.2).

The extent of VS consumption is seen more clearly if it is expressed in terms of BVS (biodegradable volatile solids) consumption. This was done in figure 5.15, using the BVS content assumed in this work for the compostable fraction of MSW as a reference (0.62 - section 2.2.6).

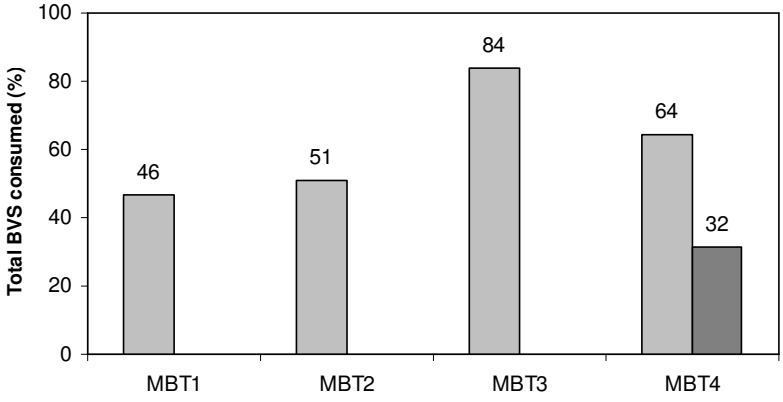

Figure 5.15. Total BVS degradation in the plants studied. Values taken from the VS consumptions in the model fittings to the experimental data, for the total process time in each plant. Two situations were considered for MBT4: i) k=0.22 d^{-1}, 64% BVS consumed; ii) k=0.082 d^{-1}, 32% BVS consumed (section 5.2.1).

MBT3 achieved a degradation of 84% of the total BVS, much higher than in any other plant.

5.2.4 Optimization of the plants

Once the diagnosis of the plants is completed (section 5.2.3), it is important to know how far one could get if these plants were operated at optimum conditions. It is also important to identify the environmental factors upon which one should preferentially act for the optimization of each plant. This was the sixth action of this work.

The procedure adopted in this section involved the modification of the environmental factors in consideration, in order to simulate the optimization of the operating conditions in the studied plants. Definition of the optimized conditions was made trying to be as realistic as possible, in the sense that these conditions can be reachable. The temperature of the input material was considered an intrinsic property of the system because, in practice, it is difficult to change. In addition, it was attempted to respect post-composting requirements, i.e., sufficiently low MC values in the final compost were defined, in order to enable a good performance of the contaminants' separation equipment in the post-composting treatment step.

It should be noted that the defined set of optimized conditions, although appearing to be reasonable and attainable, can not be fully supported. A higher support would require the closure of the energy balance of the process, but this was out of the scope of this work. In addition, this optimization study assumes that all the composting material in each time period considered is at the optimized conditions defined, although in real systems there is always some heterogeneity in terms of environmental conditions.

FAS was not changed in the optimized scenarios, in relation to the real conditions, as the latter were not limiting for this parameter, and therefore FAS patterns are not shown here. The experimental and the optimized profiles of the environmental conditions (T, MC and $[O_2]$) are presented in figures 5.16 – 5.18.

In the optimized T scenarios (figure 5.16), T rose roughly at the same speed as for the experimental data, but it was then limited by aeration to 58.6ºC, which was defined here as the value for T_{opt} (section 2.2.2). In the real conditions, T generally rose up to higher levels, in which the thermophilic microbial population was undoubtedly harmed. The exception is MBT4, where T conditions in the optimized and real scenarios are very similar.

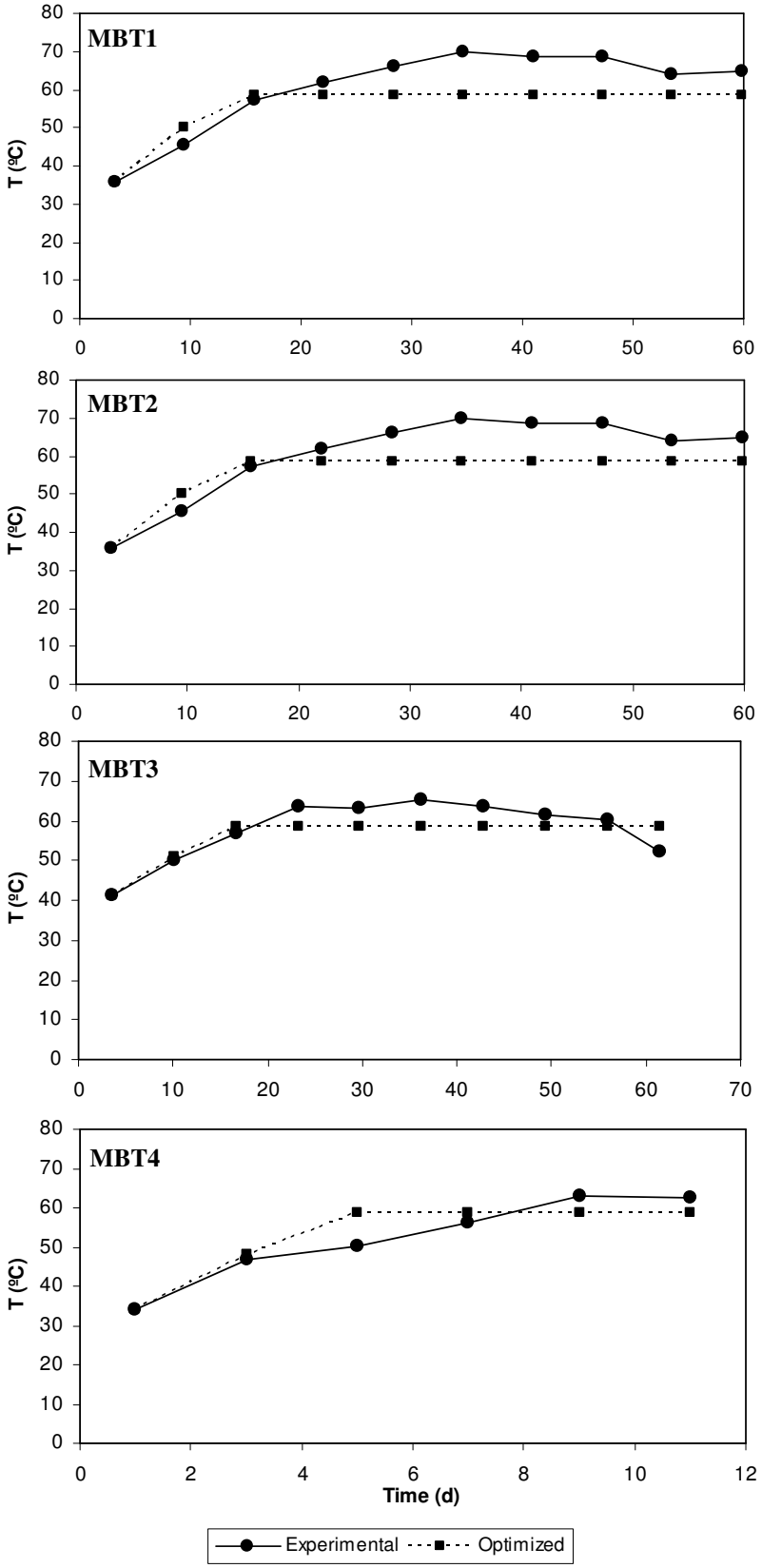

Figure 5.16. Experimental and optimized T profiles.

Moisture content (figure 5.17), in the optimized scenarios of MBT1, MBT2 and MBT3, was maintained at optimum levels by water addition, but then it was left to decrease, at the expense of the heat produced in the process and aeration, in order to reach an acceptable level for post-treatment.

In the real conditions, MC is generally low, especially in MBT1, where it reaches very low levels by the end of the process. Even the final product does not need to be so dry (24% MC, table A.2 in appendix A) for an adequate performance of the post-treatment equipment.

In the case of MBT4, MC does not differ much in the real and in the optimised scenarios. A slight decrease was imposed, though, in the final stage of the process of the optimized scenario, in relation to the experimental conditions, in order to enable a good operation of the refining equipments.

Regarding the [O_2] optimized patterns (figure 5.18), in MBT1, MBT2 and MBT4 these are rather more favourable than in the real conditions, especially in the first stages of the process. In MBT3, the optimized patterns are very similar to the real conditions, as this parameter is already quite well managed in this plant.

These sets of optimized conditions result in a significant improvement in F(TOT) in the several plants (figure 5.19), and especially in MBT1. It should be noted that, in the cases of MBT2 and MBT4, there is a slightly worse performance of the optimized scenario by the end of the process. This happened because the MC of the final product was decreased in the optimised scenario, in relation to the real conditions, for the reasons already referred.

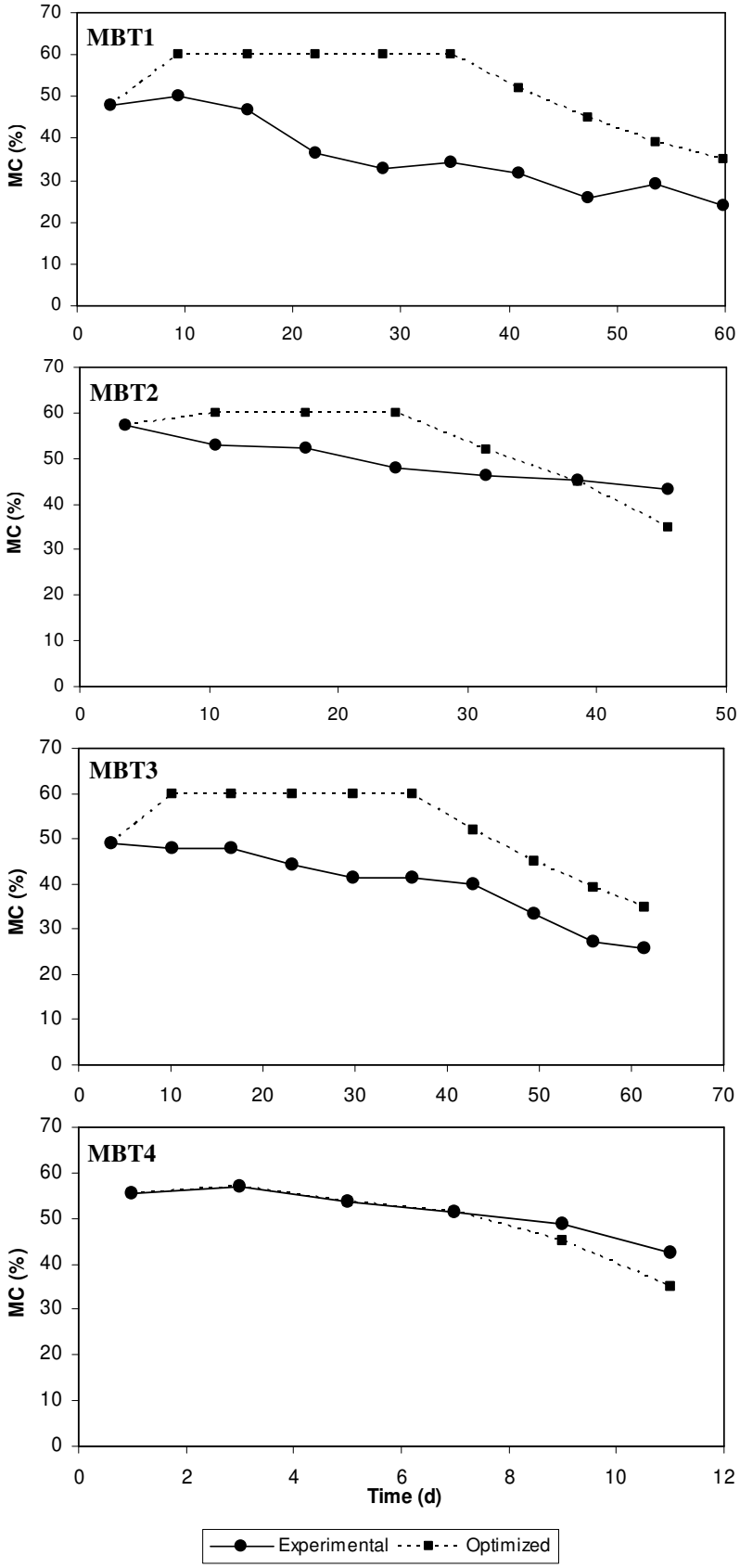

Figure 5.17. Experimental and optimized MC profiles.

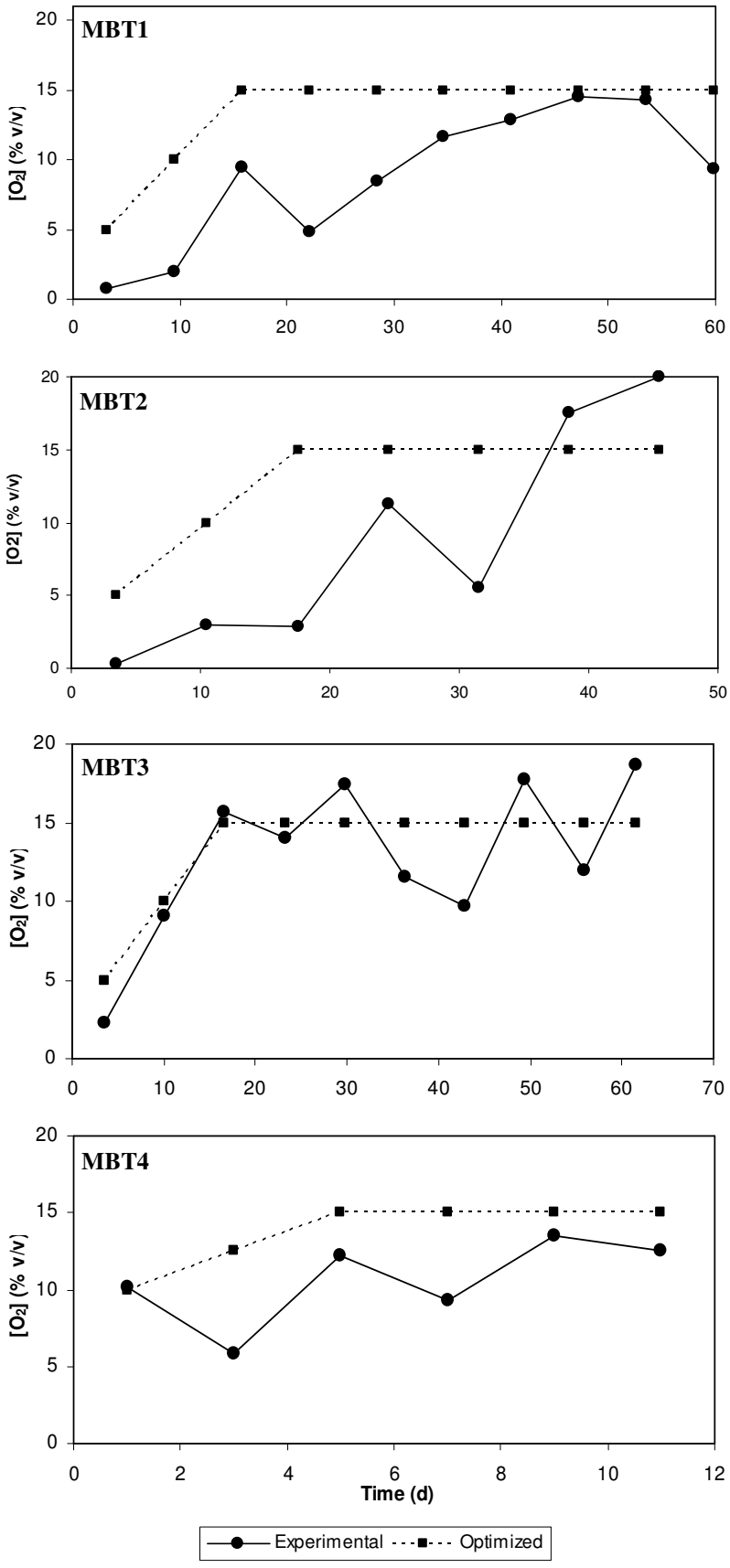

Figure 5.18. Experimental and optimized [O_2] profiles.

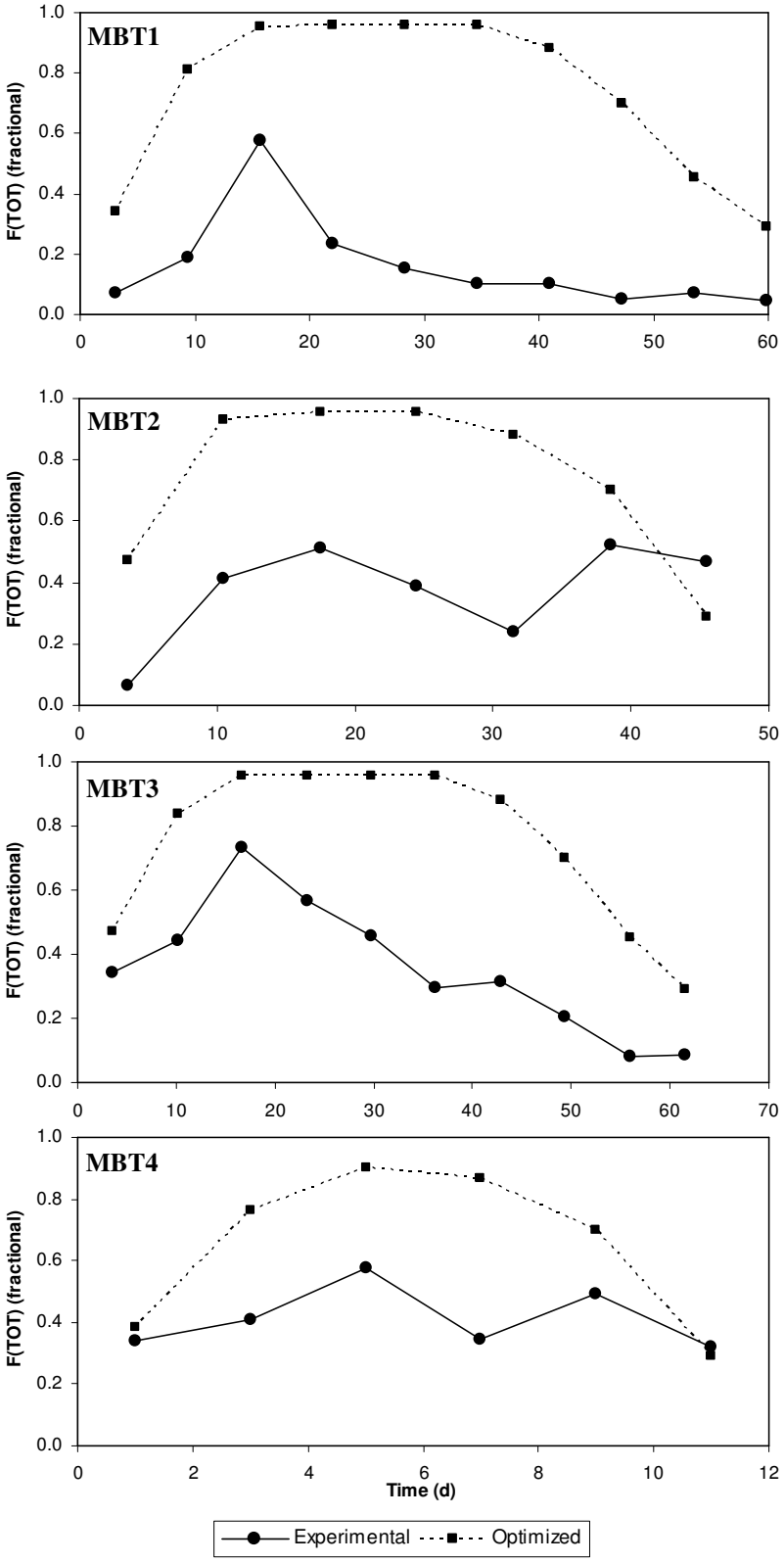

Figure 5.19. Experimental and optimized F(TOT) profiles.

Ultimately, the optimization measures are evaluated through their effect on VS consumption. Figure 5.20 illustrates the changes in VS degradation that would occur in the optimized scenario, in relation to the fitted experimental VS degradation data. The increase in VS consumption in MBT1 and MBT2 is notorious, and gives an idea about the efficiency improvements that can be made in these plants. On the contrary, in MBT3 and MBT4 the VS consumption increases are not so significant.

It is also interesting to evaluate the isolated effect of the optimization of each factor at a time. The results are presented in figure 5.21.

In MBT1, MC is the environmental factor which, individually, causes a higher improvement in VS consumption, followed by $[O_2]$ and T; FAS, as was not subject to optimization, causes no effect. This means that the onset of a strict moisture monitoring programme and control by water addition would have a great impact on process performance in this plant. Water addition should be carried out as far in the process as possible, in order to maintain favourable MC levels as long as possible, not forgetting that an appropriate MC level for post-treatment must be achieved in the final product. Increased aeration in the late stages of the process can aid in a faster MC reduction. Water addition to the composting material should ideally be made during the turning operations, and it happens to be the case that the composting system in this plant is already prepared for this. Therefore, the implementation of this measure is only dependent on the availability of water and on the instruction of the process manager for executing this measure.

T and $[O_2]$ optimization also have a significant effect on process performance in MBT1, although not as high as MC. T and $[O_2]$ optimization should be accomplished by implementation of a strict monitoring programme and control by aeration, and possibly by addition of a bulking agent to the waste, like, e.g., shredded green waste, which is already available in the plant. Although there are almost no FAS limitations, the bulking agent would improve the structure of the composting material even further, and thus help to increase the efficiency of aeration, both in terms of oxygen supply and heat removal.

The optimization analysis for this plant, together with the diagnosis carried out in section 5.2.3, illustrate how poor process management can hamper microbial activity from proceeding as required by a good composting practice.

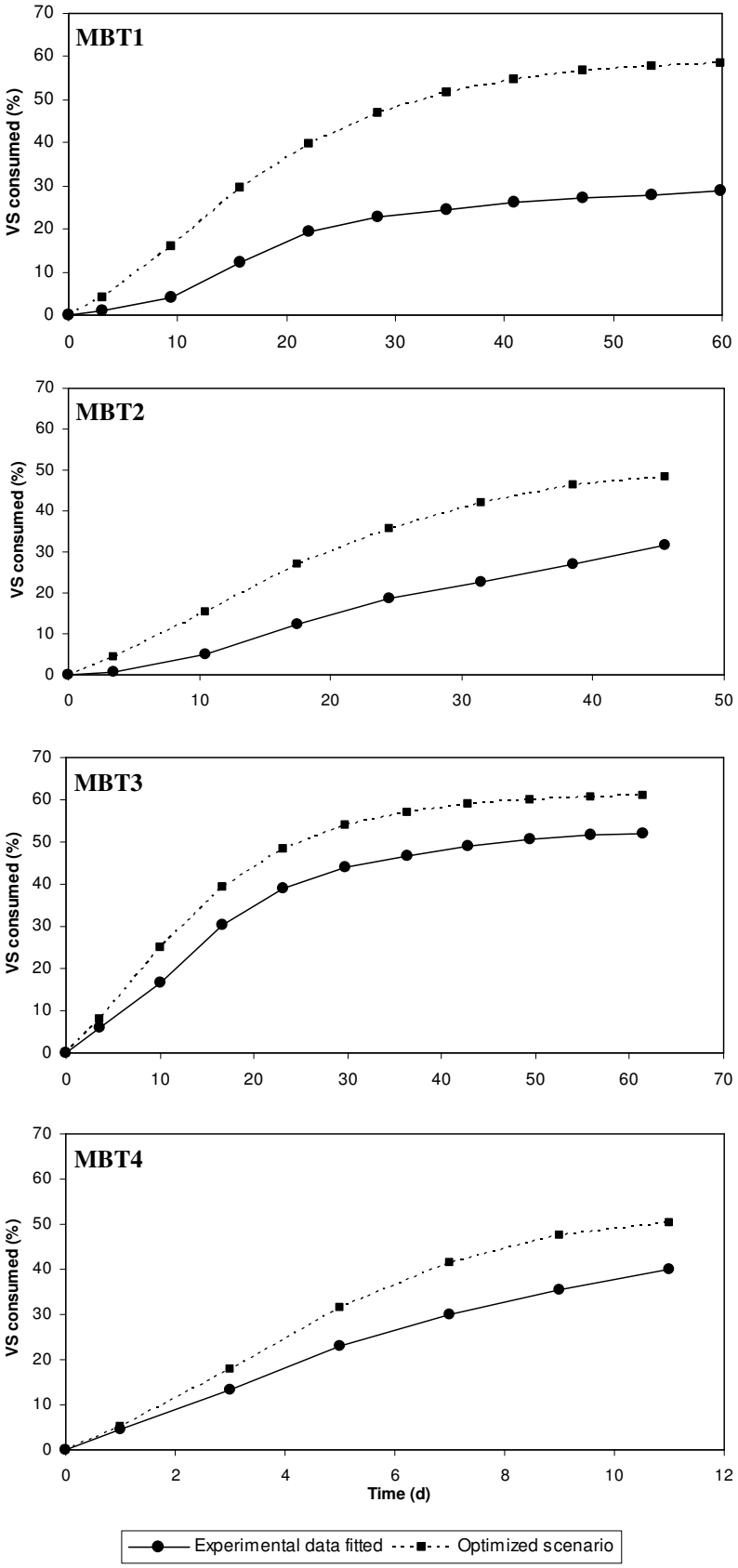

Figure 5.20. VS degradation patterns of the experimental fitted data and in the optimized conditions scenarios. For MBT4, k was considered to be 0.22 d^{-1} (section 5.2.1).

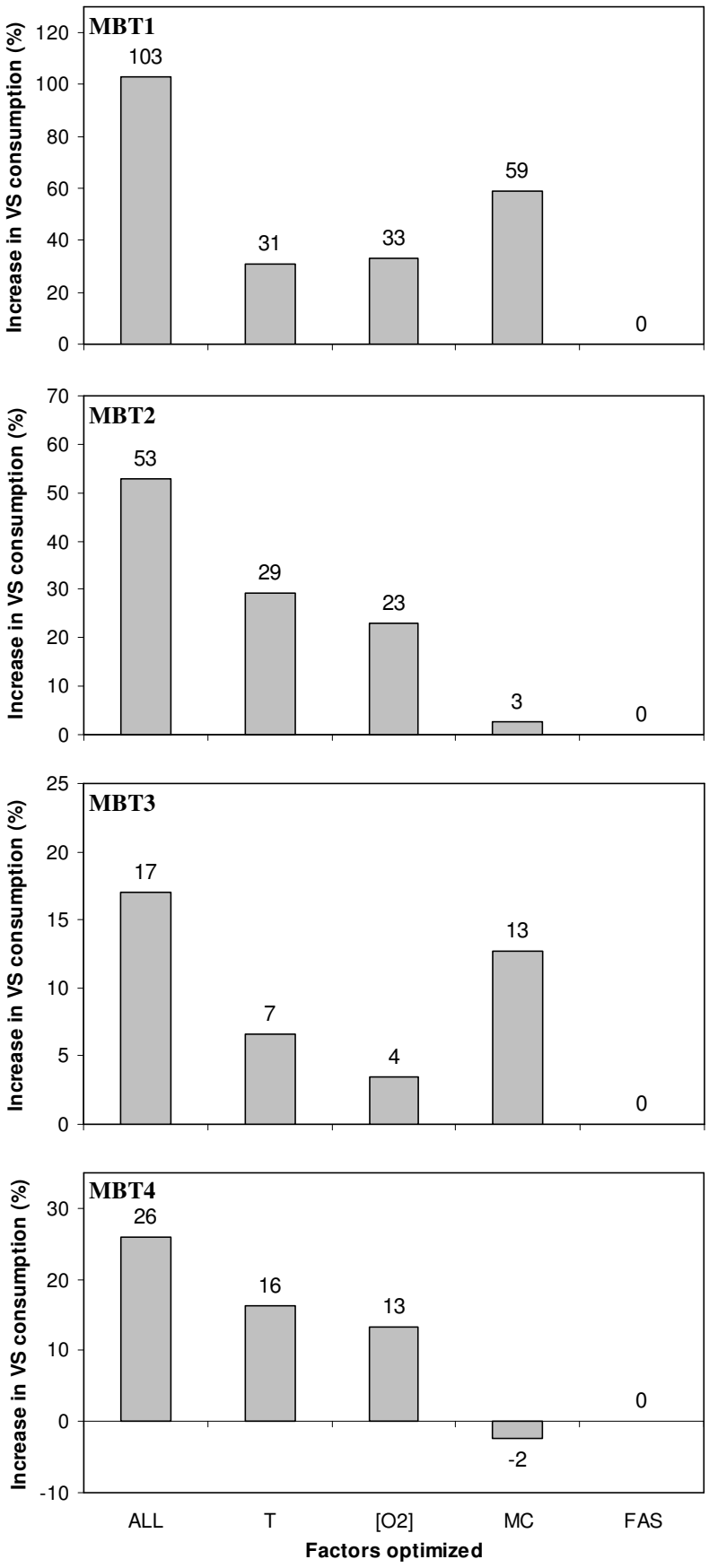

Figure 5.21. Results of the optimization of all environmental factors and of each one at a time, in terms of increase in VS consumption. For MBT4, k was considered to be 0.22 d^{-1} (section 5.2.1).

In MBT2, T and [O_2] are the environmental factors which, individually, cause a bigger improvement in VS consumption, followed by MC which, by itself, causes almost no improvement. As such, optimization efforts should concentrate on T and [O_2] optimization. As mentioned for MBT1, T and [O_2] optimization should be accomplished by improving monitoring and control by aeration, and possibly by addition of a bulking agent to the waste, like, e.g., shredded green waste. Introduction of ventilation in zone 1 is another measure that should favour the [O_2] pattern and the process as a whole. The inexistence of ventilation in this zone is likely to slow down the biological process, which was initiated in the rotary drums. One week of residence time in this zone, with a deficient oxygen supply, causes the aerobic biological process to be put in stand-by until the material is displaced to the aerated area. Furthermore, the favouring of anaerobic conditions makes the switching to aerobic conditions more difficult and slower.

The MC of the output composted material is slightly high for a good post-treatment efficiency. Further drying of the final product is thus desirable and can be achieved by increasing the ventilation in the final zone(s). If this measure is not sufficiently effective, aeration can be changed from negative to positive in the last one or two zones, as positive aeration is significantly more effective in drying the product (Haug, 1993).

One final note goes to the operating capacity of the plant, which at the time of this study was almost double in relation to the nominal capacity, and should be a major object of attention. The approximation of the operating capacity to the nominal capacity would have significant improvements in the composting process, namely:

- The residence time would be longer, allowing the achievement of a better stabilized final product;
- Pile size (2.5 m, at the time of the study) could easily be reduced, which would facilitate T and [O_2] control;
- The longer residence time in the rotary drums that would result would speed up the start of the aerobic process and increase the organic matter loss at this stage. At the same time, it would cause the output product from the drums to have smaller particle size and be drier, thus leading to a higher incorporation of organic matter in the composting material.

This latter point was actually achieved after our study, but with a different solution – the installation of a third rotary drum. The problems in the composting park remain, though, with the real capacity being much greater than the nominal capacity.

In the case of MBT3, MC is the environmental factor which, individually, causes a higher improvement in VS consumption, followed by T and [O_2]. However, optimization in this

plant does not lead to a significant increase in VS degradation, as the plant is already well operated, in practice. Notwithstanding, some optimization can be accomplished through a better control of MC by water addition to the composting material, which is anyway already performed in this plant, together with a good monitoring programme.

T management can also be slightly improved, by aeration control, in order to prevent the achievement of T values above the optimum range.

In this plant, a small percentage of bulking agent is already added to the composting material. A good material structure, together with an efficient aeration control, is effective in keeping the system without much limitation in [O_2]. An increase in the amount of bulking agent would, in any case, be beneficial for process management, as it would help in achieving higher oxygen levels from the very beginning and in reducing the small heterogeneities in aeration caused by the aeration system.

The results obtained here strengthen the conclusions drawn before (section 5.2.3) about the good composting process management in MBT3.

Regarding MBT4, this represents a special case, in this set of plants, as process duration is very short in relation to the others, i.e., 12 days *versus* 49-63 days. In this plant, T and [O_2] are the environmental factors which cause a higher improvement in VS consumption. Regarding MC, a negative effect was obtained, i.e., the proposed alterations harmed the biological process. This was, however, necessary, in order to improve the operation of the post-treatment equipments.

Anyhow, optimization in this plant does not lead to a significant increase in VS degradation, as the plant is already well operated, in practice, from the stand point of the management of environmental conditions. It should be mentioned, though, that process management in this plant is much easier than in the others. Due to the much shorter process time and the high material turning frequency, the occurrence of limiting environmental conditions is made more difficult. The disadvantage is that the achievement of a well-stabilized final product is precluded by such a short process time.

Notwithstanding, some optimization can be accomplished through a better control of aeration and possibly by the use of a bulking agent, in order to improve T and [O_2] conditions along the process. The increase in the air supply would allow achieving higher oxygen concentration values, which would be likely to speed up the organic matter degradation process. This is reinforced by the observation that, even though mean oxygen concentration values are considered satisfactory, measurements in particular days were low in part of some of the zones monitored (appendix A, table A.21).

As mentioned, the MC of the final product may be too high for the post-treatment equipment efficiency and maintenance costs. Further drying can be achieved by increasing the air supply in the last one or two zones, and eventually by switching the aeration system in these final zones from negative to positive.

Last, but not least, a note goes to the operating capacity of MBT4, which, like MBT2, is around double the nominal capacity. Analysis of the results from the biological process as a whole reveals that the main reason for the low degree of stabilisation of the final product has to do with the under-dimensioning of the plant in relation to the amount of residues received, rather than to an incorrect biological process management. The fact that the plant is being operated at double its nominal capacity causes the residence time of the material in the composting park to be reduced from 24 days to about 12-14 days, and this is the main problem that should be dealt with first.

Overall, it can be seen that there is a very big margin for process management improvement in some of the full-scale systems studied, namely around 103% for MBT1 and around 53% for MBT2. The improvements obtained in the optimization scenarios correspond to the VS degradation profiles presented in figure 5.22.

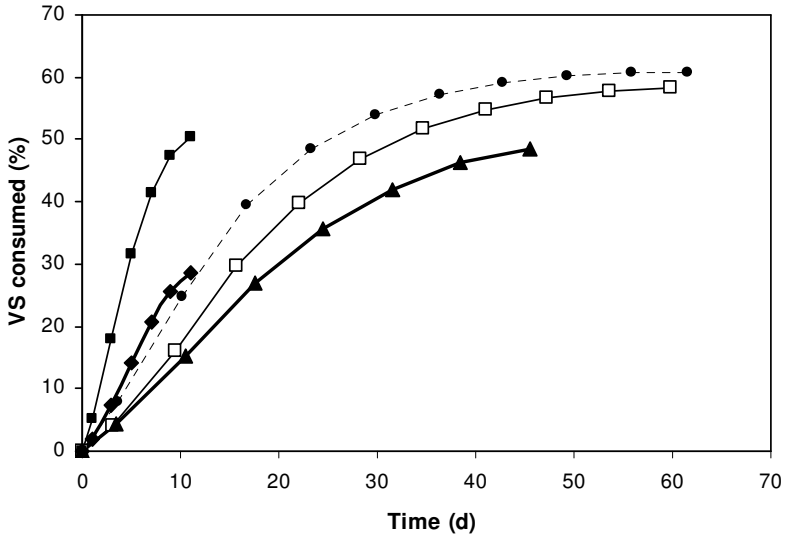

Figure 5.22. VS degradation patterns in the optimized scenarios for the plants studied. MBT4a: k=0.22 d^{-1}; MBT4b: k=0.082 d^{-1} (please refer to section 5.2.1).

VS degradation is fastest in MBT4a, whereas the performance of MBT1, MBT2 and MBT3 are closer here than the ones obtained from the experimental measurements fit (figure 5.14). However, if, a k of 0.082 d^{-1} is considered instead of 0.22 d^{-1}, as discussed in section 5.2.1, then the VS degradation pattern corresponds to MBT4b in figure 5.22. In this case, the VS degradation patterns are much closer in the four plants studied. However, some differences remain which are mostly due to differences in the k values obtained for each plant. The fact

that the environmental conditions were optimised causes the VS degradation patterns to be more dependent on the intrinsic characteristics of each system, i.e., on k.

Finally, it should be noted that the above-mentioned optimization scenarios would undoubtedly increase the degree of stability of the resulting composts. However, conditions for further maturation would have to be created in the after post-treatment phase, i.e., the cure phase, if a highly stabilised product is to be obtained. This is demonstrated by the results obtained for MBT3. This plant had the best process management performance in this study and it produced the most stable compost. Additionally, the optimization scenario for MBT3 does not lead to a great improvement in VS degradation (figures 5.20 and 5.21); nevertheless, the compost produced is still degree I in the self-heating test (table 5.2).

5.3 Comparison of k estimates with k obtained from the literature

The simulation model adopted in this work was submitted to a further test: the comparison of k values obtained from section 5.2.1 with k data obtained from the literature, both for lab-scale and for full-scale studies, which used similar composting materials to the ones studied here. This was the seventh action of this work. It should be noted that k values obtained from the literature were also corrected for the environmental conditions in consideration.

The aim of this test was checking if the simulation model used in this work accounts for all the corrections that have to be made in order to convert k to a universal, comparable basis. In other words, if the composting rate of similar waste materials is influenced only by T, MC, $[O_2]$ and FAS, then the k estimates from the selected studies should be very similar.

A procedure for k correction similar to the one used here was already utilized in an earlier work by Mason (2008b), except that the reaction rate constants were only corrected for T, although the consideration of MC and $[O_2]$ was also suggested by this author. Mason (2008b) corrected k for T for the purposes of the evaluation of substrate degradation profiles obtained at varying T conditions. For the purposes of the present work, correction of k for all the environmental factors is necessary. However, because data on the environmental conditions was usually scarce in the literature, assumptions often had to be made about the data for one or more of the environmental factors data in consideration, based on the information given by the authors. Therefore, in addition to the similarity of composting materials criterion, the studies selected from the literature for this analysis were those where the assumptions that had to be made were considered to be reasonable. Selected studies are those presented in tables 5.9 and 5.10. k for MBT4 was not considered in this analysis, due to the uncertainty around this value (section 5.2.1).

Table 5.9. Full-scale studies selected from the literature for k analysis. Environmental factors' data available for each study, as well as the assumptions that were made for the purpose of this analysis.

Reference / system		Data availability				Assumptions
		T	MC	$[O_2]$	FAS	
Fricke & Mueller, 1999	HV 1-1	A	A	A	NA	FAS was assumed to be non-limiting, as the composting materials in these studies are similar to the ones studied in this work, for which no FAS limitation was observed (section 5.2.3.1).
	HV 2	A	A	A	NA	
	HV 3	A	A	A	NA	
	ROCO 1	A	A	A	NA	
	ROCO 4	A	A	A	NA	
	Biodegma	A	A	A	NA	
	Kessler & Luch	A	A	A	NA	
	WGV	A	A	A	NA	
Adani *et al.*, 2000		A	A	A	NA	

A – available; NA – not available.

Table 5.10. Lab-scale studies selected from the literature for k analysis. Environmental factors' data available for each study, as well as the assumptions that were made for the purpose of this analysis. (To be continued)

Reference	Data availability				Assumptions
	T	MC	$[O_2]$	FAS	
Keener *et al.*, 1997	A	A	NA	NA	$[O_2]$ assumed to be 10% because the reactors had forced aeration; FAS was assumed to be non-limiting, as the composting materials in these studies are similar to the ones studied in this work, for which no FAS limitation was observed (section 5.2.3.1);
Richard, 1997	A	A	A	NA	FAS assumed to be non-limiting because a bulking agent was added and because the $[O_2]$ values were high;
Hamoda *et al.*, 1998	A	A	NA	NA	$[O_2]$ assumed to be 10% due to the configuration of the system and the small amounts of material used in the assays; FAS was assumed to be non-limiting, as the composting materials in these studies are similar to the ones studied in this work, for which no FAS limitation was observed (section 5.2.3.1);
Namkoong *et al.*, 1999	A	NA	NA	NA	MC assumed to be 55%, as the authors mention this was maintained in between 50 and 60%; $[O_2]$ assumed to be 10% due to the configuration of the system and the small amounts of material used in the assays (no forced aeration); FAS assumed to be non-limiting, taking into account the type of waste used;
Shin *et al.,* 1999	A	NA	A	NA	MC assumed to be 55%, as this was the initial MC of the mix and because the air for forced aeration was humidified before entering the reactor; FAS assumed to be non-limiting because a bulking agent was used and because the $[O_2]$ levels were high;
Adani *et al.*, 2000	A	A	A	NA	FAS was assumed to be non-limiting, as the composting materials in these studies are similar to the ones studied in this work, for which no FAS limitation was observed (section 5.2.3.1);
Bari *et al.*, 2000	A	NA	NA	NA	MC was assumed to be 53%, because the initial and final values were 53.4% and 52.5%, respectively; $[O_2]$ – the authors mention that O_2 levels were controlled and maintained in appropriate levels, by forced aeration; a value of 15% was assumed, which seems to be reasonable taking into account Bari & Koenig (2001), where the same system is studied and $[O_2]$ data is available; FAS assumed to be non-limiting because paper and sawdust, which have a bulking agent effect, were used in the mix;

A – available; NA – not available.

Table 5.10. Lab-scale studies selected from the literature for k analysis. Environmental factors' data available for each study, as well as the assumptions that were made for the purpose of this analysis. (Continuation)

Reference	Data availability				Assumptions
	T	MC	$[O_2]$	FAS	
Huang *et al.*, 2000	A	NA	NA	NA	MC – initial MC was 70%, and it was mentioned that it was maintained in between 66% and 72%; an average value of 69% was considered; $[O_2]$ considered to be 15%, which should be reasonable considering that a bulking agent is used in the mix and that the system had forced aeration; FAS assumed to be non-limiting because rice husks were used as a bulking agent;
Beck-Friis *et al.*, 2001	A	A	A	NA	FAS assumed to be non-limiting because straw was used as a bulking agent;
Smars *et al.*, 2002	NA	NA	NA	NA	T – it was assumed to be 55ºC, the T set point control; it was further assumed that T at day 5 was already 55ºC, and that it was maintained around this value until day 15, which should be correct considering Beck-Friis *et al.* (2001), where composting trials with the same materials and reactor system were carried out; MC – assumed to be non-limiting, i.e., F(MC)=1, because the authors mention that MC was controlled by water addition; $[O_2]$ – the system used had forced aeration and analysed the output gas for $[O_2]$; 16% was assumed, the same value the authors use in other works with the same materials (Beck-Friis *et al.*, 2001); FAS assumed to be non-limiting because straw was used as a bulking agent;
Beck-Friis *et al.*, 2003	A	NA	A	NA	MC – there is no information, therefore the initial MC (65%) was considered as the operating MC; FAS assumed to be non-limiting because straw was used as a bulking agent;
Komilis, 2006	A	NA	NA	NA	MC – it was assumed to be 57.5%, as initial MC was 55-60%, and air was warmed up and humidified before entering the reactor; besides, the author refers that MC was controlled by water addition, when necessary, in order to maintain composting conditions close to optimum; $[O_2]$ was assumed to be 15%, as the author mentions it was kept above this value; FAS assumed to be non-limiting because aluminium packing material was used as a bulking agent;
Briski *et al.*, 2007	A	NA	NA	NA	MC in the middle stages was assumed to be 61.3%, the average between the initial (64.4%) and the final MC (58.2%); $[O_2]$ considered to be 15%, which should be reasonable considering that a bulking agent is used in the mix and that the system had forced aeration; FAS assumed to be non-limiting because poly vinyl chloride filings were used as a bulking agent;
Eklind *et al.*, 2007	A	A	A	NA	FAS assumed to be non-limiting because straw was used as a bulking agent;

A – available; NA – not available.

k' (uncorrected k) was also estimated by fitting to VS degradation data using equation 2.9, for comparison purposes. This is the reaction rate constant uncorrected for the environmental conditions, i.e., T, MC, [O_2] and FAS, and corresponds to the first-order reaction rate constants normally found in the bibliography. It differs from k' presented in section 5.2.3.2, because in this case information on environmental conditions was not taken into account for calculation. Here, k' was estimated only from the VS degradation with time. The k' estimate is hence a constant value for each study.

Both k and k' are properties of the system, and both give useful, but different, information. In this work, the corrections for the environmental conditions allow the separation of k' in two components: i) F(TOT), which is a direct measure of the operation performance (section 5.2.3.1); ii) k, the corrected rate constant, which is a constant specific to each plant, and is therefore much more independent from the operator (section 5.2.1). k tells us more about the system itself, which includes the composting material and the system characteristics, but excludes the operator's performance, regarding the management of the environmental conditions T, MC, [O2] and FAS. It gives us an idea about how far in the stabilization process (VS consumption) one can get in each plant, i.e., the limit up to where one could get if the environmental conditions in consideration were all optimal, 100% of the time. In practice, the actual closeness to this limit then depends on the operator's skills and performance. For example, if k is high, and the process operation is good, one gets far in the stabilization process. If k is high, but operation is poor, the VS consumption will be small. If, on the other hand, k is small, one will not go far in the process, even with a good operation.

k and k' values in analysis are presented in tables 5.11 and 5.12, together with a description of the material and the composting system used in each study. The R^2 of the model fit to the data is also presented, for the situations where the k estimates from the authors where either not calculated or not used. k and k' values are presented graphically in figures 5.23 – 5.25.

Table 5.11. k and k' values estimated for full-scale MBT plants. Source data was, in all cases, VS data.

Reference	Material	k'(d^{-1})	k (d^{-1})	R^2 of the model fit	[BVS_o] (fractional rel. VS)*	RT (d)**	System description
MBT1 - This work	MSW treated mechanically; fraction<80 mm	0.013	**0.063**	0.96	0.62b	63	Koch semi-open system, with positive forced aeration, turning every 6.3 days
MBT2 - This work	MSW treated in a rotating drum aprox. 24 h, then sieved <25 mm	0.019	**0.043**	0.97	0.62b	49	Vinci-Environment semi-open system, with positive forced aeration, turning every 7 days
MBT3 - This work	MSW treated mechanically; fraction<80 mm	0.039	**0.082**	0.96	0.62b	59,5	Koch semi-open system, with positive forced aeration, turning every 6 days
Fricke & Muller, 1999	MSW treated in a rotating drum for 12-20 h, then sieving under 40 mm	0.019	**0.056**	0.96	0.71a	56+288	HV 1-1: Open air process; 8 weeks high-rate composting; 43 weeks curing in unventilated, static piles
	MSW treated in a rotating drum for 12-20 h, then sieving under 40 mm	0.014	**0.041**	0.96	0.71a	112+320	HV 2: Open air process; 16 weeks high-rate composting; 45 weeks curing in unventilated, static piles
	MSW treated in a rotating drum for 12-20 h, then sieving under 40 mm	0.016	**0.074**	0.96	0.56a	28+404	HV 3: Open air process; 4 weeks high-rate composting; 57 weeks curing in unventilated, static piles
	MSW treated in a rotating drum for 12-20 h, then sieving under 40 mm	0.023	**0.043**	0.990	0.69a	116	ROCO 1: Closed container, high control system; 17 weeks high-rate composting
	MSW treated in a rotating drum for 12-20 h, then sieving under 40 mm	0.054	**0.064**	0.997	0.62a	129	ROCO 4: Closed container, high control system; 18 weeks high-rate composting
	MSW	0.032	**0.041**	0.97	0.67a	83	Biodegma: Forced aeration system
	MSW	0.058	**0.112**	0.98	0.57a	78	Kessler & Luch - forced aeration system
	MSW	0.010	**0.038**	0.89	0.62b	83	WGV - 2 weeks forced aeration, 7 weeks without aeration, then 2 weeks with forced aeration
Adani *et al.*, 2000	MSW treated mechanically; fraction<50 mm	0.044	**0.077**	0.94	0.62b	37+79	First 37 d - continually aerated windrow, turning every 2 days; then curing phase

*[BVS_o] was estimated from the authors' data in those situations where enough information existed for that estimate to be made (marked with a). Otherwise, [BVS_o] was fixed at 0.62 (marked with b). (cf. section 4.2.6)

**When two periods are presented, the first corresponds to a high-rate composting stage, and the second to a cure stage.

Table 5.12. k and k' values estimated for lab-scale studies selected from the bibliography. (To be continued)

Reference	Material	k' (d^{-1})	k (d^{-1})	R^2 of the model fit	[BVS_o] (rel. VS)*	RT (d)**	Source data for k estimation	System description
Keener *et al.*, 1997	MSW	0.051	**0.073**	-	-	55	DM	Lab-scale reactor of 200 l, with forced aeration; mixing every 7 d
	MSW	0.083	**0.092**	-	-	55	DM	
	MSW	0.024	**0.027**	-	-	-	DM	
	MSW	0.032	**0.068**	-	-	-	DM	Lab-scale reactor of 200 l, with forced aeration; mixing every 3.4 d
Richard, 1997	Dry dog food + maple wood chips : compost; 9 : 1 (dry weight basis)	0.095	**0.30**	0.98	0.38a	30	$C\text{-}CO_2$ emissions	Insulated lab-scale 1500 l reactor, with forced aeration (air heated and humidified), 1 revolution every 30 min
Hamoda *et al.*, 1998	MSW was treated in a hammer mill, strange materials (glass, stones, plastic) removed, and then sieved below 50 mm; MSW : compost; 10:1 (dry weight basis)	0.011	**0.021**	0.93	0.62b	15-18	VS, data from series II, 40 mm particle size	2 l erlenmeyers (0.5 Kg samples) at fixed T, with aeration (moist air) and daily manual mixing
Namkoong *et al.*, 1999	Food waste recipe - 15% cereals, 50% vegetables; 20% meat or fish; 15% fruits + 5% wet weight mature compost	0.51	**2.84**	0.91	0.65a	80	VS	2 l beakers at 25ºC, MC: 50-60%; daily mixing, no aeration;
	Food waste recipe - 30% cereals, 41% vegetables; 17% meat or fish; 12% fruits + 5% wet weight mature compost	0.63	**3.53**	0.995	0.78a	80	VS	
	Food waste recipe - 11% cereals, 38% vegetables; 40% meat or fish; 11% fruits + 5% wet weight mature compost	0.47	**2.65**	0.995	0.51a	80	VS	
Shin *et al.*, 1999	Garbage from cafeteria (vegetables, meat, cooked rice, eggs, bread, etc) : woodchips; 8.7:2.9 (wet weight basis); no size reduction	0.10	**0.33**	0.96	0.47a	18	DM, data from control test	8.7 l insulated reactor (1.3 Kg sample), with forced aeration and humidification of air; daily mixing
Adani *et al.*, 2000	MSW treated mechanically in a MBT plant; fraction<50 mm	0.071	**0.20**	0.81	0.62b	37+79	VS	First 37 d - composting in a 150 l adiabatic reactor, with forced aeration; then 79 d in a non-ventilated heap, turned every 4 to 5 d, with water addition; 26 Kg sample

*[BVS_o] was estimated from the authors' data in those situations where enough information existed for that estimate to be made (marked with a). Otherwise, [BVS_o] was fixed at 0.62 (marked with b). (cf. section 4.2.6)

**When two periods are presented, the first corresponds to a high-rate composting stage, and the second to a cure stage.

Table 5.12. k and k' values estimated for lab-scale studies selected from the bibliography. (Continuation)

Reference	Material	k' (d^{-1})	k (d^{-1})	R^2 of the model fit	[BVS_o] (rel. VS)*	RT (d)**	Source data for k estimation	System description
Bari *et al.*, 2000	Food waste from student canteen shredded < 10-15 mm : paper : sawdust; 75:12.5:12.5 (wet weight basis)	0.070	**0.16**	0.993	0.67a	23	VS, data from test 5	Insulated reactor with 200 l, forced aeration, no turning
Huang *et al.*, 2000	Vegetable waste from a vegetable market<1-2 cm : rice husks; 6:1 + 30% compost (dry weight basis)	0.20	**0.24**	0.9998	0.42a	15	VS	Temperature-controlled reactor with forced aeration – 5.3 Kg run
Beck-Friis *et al.*, 2001	Household source separated waste triturated (<13 mm) : chopped wheat straw; 1:0.3 (dry weight basis)	0.32	**0.34**	-	0.64a	21-30	C-CO_2 emissions, regime B	Insulated 200 l reactor, with aeration, daily semi-manual mixing
Smars *et al.*, 2002	Household source separated waste triturated : chopped wheat straw; 3:1 (dry weight basis) (<28 mm)	0.30	**0.31**	0.9988	0.65a	15	C-CO_2 emissions, regime I	Insulated 200 l reactor, with aeration, daily semi-manual mixing
Beck-Friis *et al.*, 2003	Household source separated waste triturated (<13 mm) + chopped wheat straw	0.30	**0.32**	0.994	0.62a	25	C-CO_2 emissions, [O_2]=16% trial	Insulated 200 l reactor, with aeration, daily semi-manual mixing
Komilis, 2006	Food waste recipe: milk + cooked pasta + hamburger + lettuce + raw potatoes + carrots in equal amounts (wet weight basis) + 10-15% (v/v) aluminium packing material	0.076	**0.088**	0.97	0.70a	91	C-CO_2 emissions	25 l lab reactors at 55ºC, with forced aeration
Briski *et al.*, 2007	Food waste recipe (Carrot, potato, cabbage, onion, lettuce salad, apple, peach, orange and kiwi scraps in 5x10 mm peaces) : uncultivated soil; 3 : 2; poly (vinyl chloride) filings used as a bulking agent	0.52	**0.82**	0.98	0.88a	14	C-CO_2 emissions	Insulated 1 l columns, with forced aeration and humidification of air
Eklind *et al.*, 2007	Household source separated waste triturated (<13 mm) + chopped wheat straw	0.33	**0.34**	0.998	0.63a	15	C-CO_2 emissions, 55ºC trial	Insulated 200 l reactor, with aeration, daily semi-manual mixing

*[BVS_o] was estimated from the authors' data in those situations where enough information existed for that estimate to be made (marked with a). Otherwise, [BVS_o] was fixed at 0.62 (marked with b). (cf. section 4.2.6)

**When two periods are presented, the first corresponds to a high-rate composting stage, and the second to a cure stage.

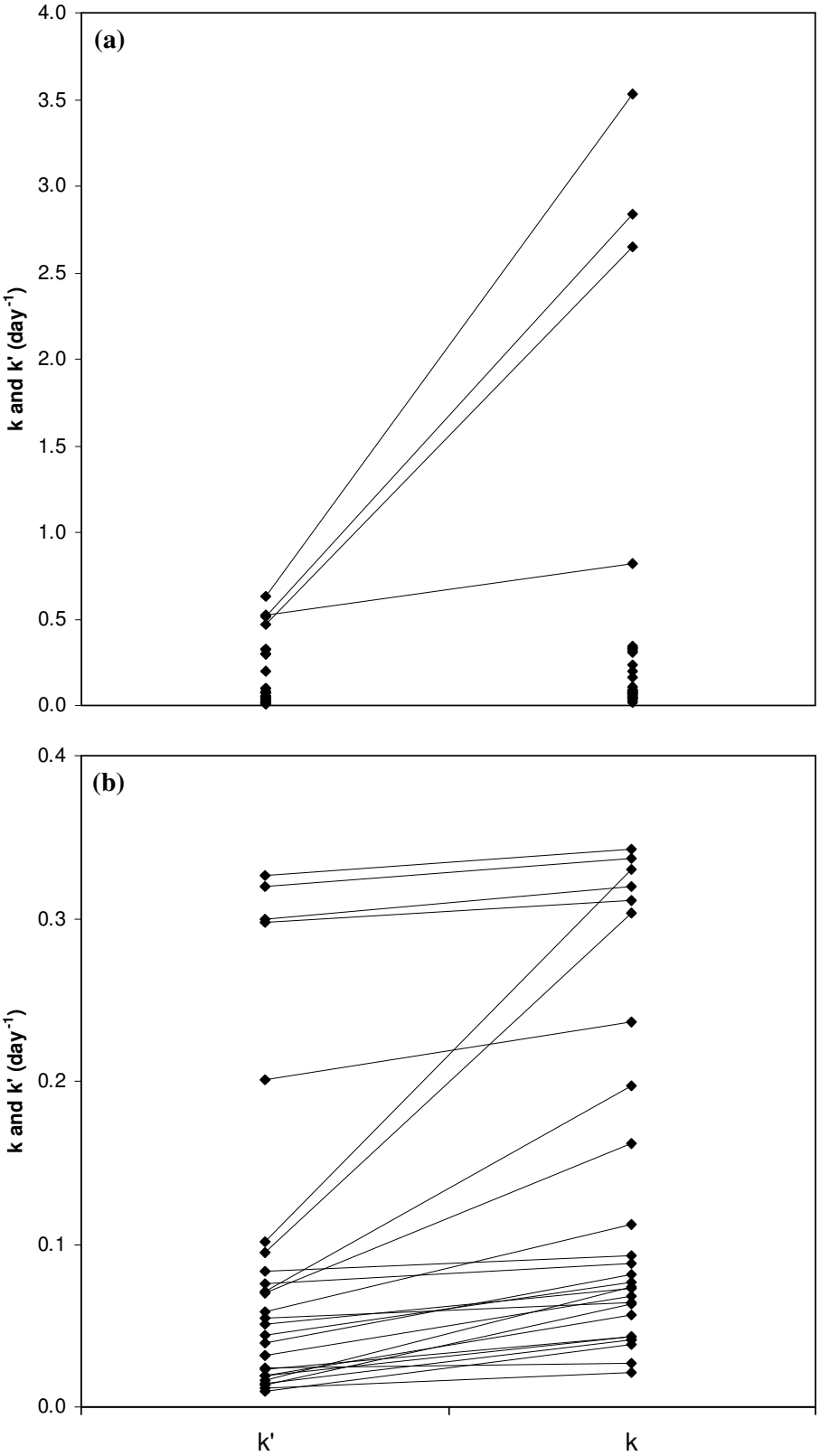

Figure 5.23. Comparison of the k' and k values in analysis, which include the plants studied in this work, and the full and lab-scale studies selected from the literature. The k and k' values correspondent to the same data were connected by straight lines: (a) all data, with k-k' correspondence for the higher range values; (b) the four highest k and k' values were excluded from this figure in order to magnify the y-axis scale.

The k', and especially the k values, obtained from the studies of Namkoong *et al.* (1999) and Briski *et al.* (2007) are quite apart from all the other values. In the case of Briski *et al.* (2007), the small particle size (5x10 mm pieces) may explain, at least partially, the high k obtained. Regarding Namkoong *et al.* (1999), the reason for the high k values may possibly have to do with the same factor, but no information about materials preparation or particle size is given by the authors.

It should be noted that, in some cases, k' is much smaller than k, as in the data from Namkoong *et al.* (1999). This has to do with the distance of the operating environmental conditions from the optimum levels – the bigger this distance, the bigger the difference between k and k'. Conversely, similar k and k' values occur in plants where operating environmental conditions are close to the optimum levels.

The k' and k values are presented in figures 5.24 and 5.25, respectively, according to the origin and the scale of the study from where they were obtained.

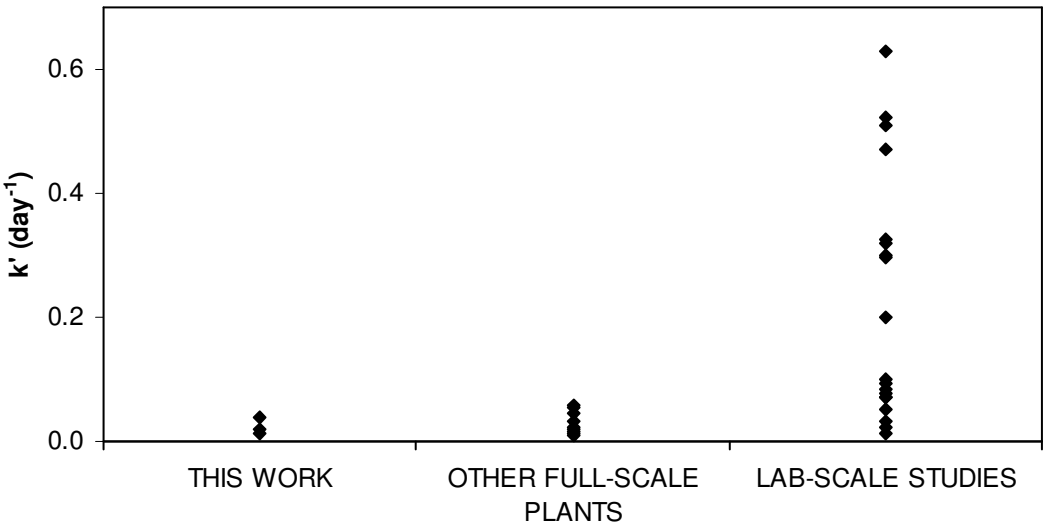

Figure 5.24. Comparison of k' values obtained in this work with k' values obtained from the literature, both for lab-scale and for full-scale studies.

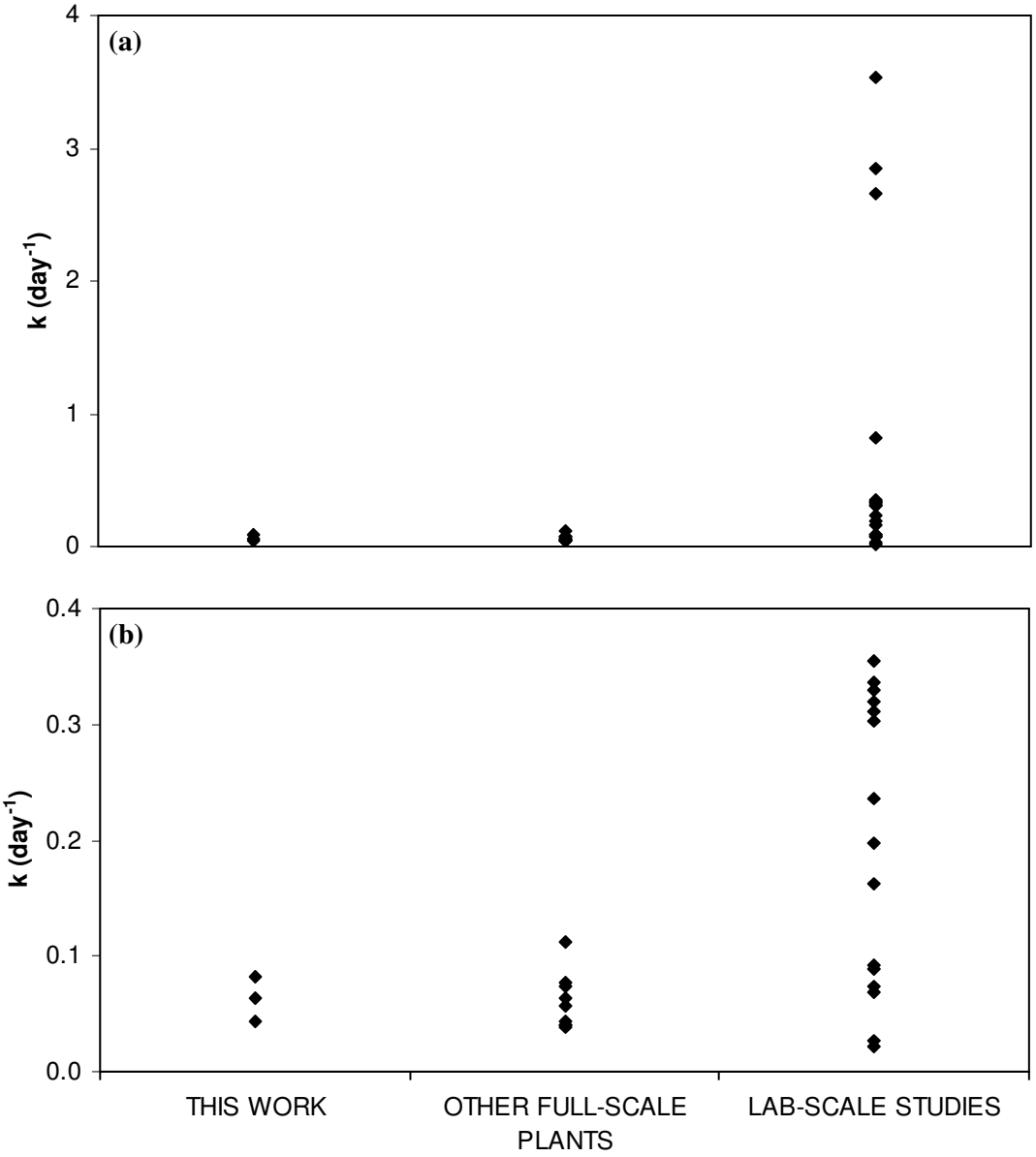

Figure 5.25. Comparison of k values obtained in this work with k values obtained from the literature, both for lab-scale and for full-scale studies: (a) all values; (b) the four highest k values obtained for the lab-scale studies were excluded in order to magnify the y-axis scale.

The analysis of the data for the kinetic constants presented above for full and lab-scale studies generated the following observations:

- k values from full-scale studies do not vary greatly;
- k variation in the lab-scale systems is much wider, and k can reach much higher values than in the full-scale systems, even though similar types of composting materials were used.

The significance of these observations is discussed in section 6.4.

6. GENERAL DISCUSSION

6.1 Quality of the experimental data

In general, the experimental data collected was of adequate quality for subsequent use in the simulation work (section 5.2.1). However, there was one particular case where scattering of experimental data was such that affected the subsequent modelling analysis. This refers to MBT4, where a notorious increase in the VS content was observed from zone 1 to zone 2 (figure 5.4(f)). This increase is obviously not possible to occur, and was the most likely cause for the substantial level of uncertainty that affected the k estimate for this plant. Two alternative k estimates were obtained for MBT4, namely 0.22 d^{-1} and 0.082 d^{-1} (section 5.2.1), which differ considerably from each other.

This indicates that more effort should have been put in the collection of VS content data, because this was the process monitoring parameter, and therefore the one for which a greater accuracy was needed.

6.2 Adequacy of the model to describe the experimental data

It was shown that the simulation model defined in section 2.2.7 described fairly well the experimental data collected in MBT1, MBT2 and MBT3, taking into consideration the R^2 values, the standard errors for the VS_i and k estimates (table 5.4), and as judged by the visual inspection of the experimental data fits (figure 5.6). There were some problems, though, in simulating MBT4 experimental data, but, as already mentioned, these where most likely due to scattering in the VS data.

Therefore, we consider that this kinetic model, based on composting research, was successfully applied to full-scale MBT plants. To our knowledge, there are no further works where this was done. Only one reference to this subject was found in the literature (Kaiser & Soyez, 2000). These authors, though, argue that: *"Some mathematic tools for plant engineering, process design and control can be adopted from similar tools in composting. Unfortunately, the system of particular processes is much more complex in MBT: additional phenomena, both of chemical and microbiological natures are involved. Consequently, there is no chance to find a procedure to calculate kinetics or dynamics of a MBT process."* However, the experimental and simulation results obtained here contradict this opinion. It was shown that application of the procedures described in this work can give us a good picture of the kinetics of full-scale MBT plants. The successfully application of this composting kinetic model to full-scale MBT plants was further reinforced by the good results of its application to other authors' data, and by the fact that the k values for all the full-scale studies analysed varied only in a limited range (section 5.3).

6.3 Diagnosis of the operation performance and evaluation of the potential for optimization in the MBT plants

The operation performance of the MBT plants under study was evaluated, as far as the maintenance of favourable environmental conditions is concerned, as well as the possibilities and the potential for improvement. Regarding the diagnosis analysis, the correction factors are a good tool to clearly identify the degree of process rate limitation at any time by any of the environmental conditions studied. The F(TOT) data gives an indication of the overall limitation to process rate, for any process time. The parameter k' goes a step further in relation to F(TOT), as it gathers information from F(TOT) and k; it indicates the actual performance of each plant along process time. Finally, the VS degradation patterns are a direct measure of process performance. Analysis of the information from these three process performance indicators is complementary and supplied coherent information for the diagnosis of the plants.

The good agreement between the diagnosis and the optimization results is to be referred. Plants that were identified as poorly managed were the ones for which the greater optimization potentials were obtained, and vice-versa.

One important feature of the diagnosis and optimization analysis as a whole is that it leads to results which are workable in the field, normally in a relatively simple manner. By changing the aeration cycles or the ventilation capacity, water addition regimes, material turning regimes, pile size, or by the use of a bulking agent, depending on which are the objects of action, one can act upon the environmental conditions accounted for in the model (T, MC, [O2] and FAS).

The results obtained here highlight the importance of having:

- Well designed systems, which allow operation close to the optimum conditions;
- Good process managers in full-scale composting systems; this point is very evident from the results of MBT1 and MBT3, because these plants are very similar both in design and in the type of waste received, but, in MBT1, the margin for improvement is around 103%, whereas in MBT3 it is only around 17%, due to a much better process management in the latter;
- Implementation of monitoring programs for full-scale composting systems; it is important to have a tool that allows plant managers to deepen their knowledge about process management, and that helps in evaluating and optimizing their performance.

Situations were identified here where poor process management compromised process performance, and hence the quality of the final compost and the impacts of the plant on the environment and surrounding populations. Overall, the profit that can be taken from the investment is compromised by poor process management practices.

It is proposed that these procedures for data collection and treatment are applied to full-scale composting plants for operation performance evaluation and optimization. This is a means of bridging the gap in between researchers and plant operators, certainly advantageous for both parts, and a way of improving the performance of full-scale plants.

A comment should also go for the cure phases in the four MBT plants. These were not studied here, but in general there was very poor, if any, process management. Compost was just stockpiled, normally in huge piles, with little further action. Appropriate management of this process stage is essential for the achievement of a high degree of maturation in the compost. These cure stages should involve: i) the maintenance of appropriate moisture levels; ii) the construction of appropriate size stockpiles, which, together with the execution of adequate turning, would allow the maintenance of T and $[O_2]$ at favourable levels. These conditions should then be maintained for a variable period of time, depending on the stability degree of the output product from post-treatment and the stability degree desired.

6.4 Comparison of k estimates with k obtained from the literature

Comparison of k values obtained for the plants studied in this work with k values estimated for data collected from the literature was carried out in section 5.3. The results of that analysis are discussed in this section.

6.4.1 k values from full-scale studies

k values from the full-scale MBT plants did not show great variation. This leads one to think that the model used here is appropriate to describe the composting process at this scale. If factors other than those included in the model have a significant effect on k, either they did not vary much in the MBT plants under study, or variations were such that compensated each other, in terms of the global effect on k.

The composting material is, in all cases, pre-treated MSW. There may be some differences in between the several MSW considered, but major differences in the composting material should come from the pre-treatment configuration in each MBT plant. The major influential factor should be the rotary drums, present in some cases, absent in others. As already mentioned, the rotary drums cause a significant size reduction in the waste, due to the constant mechanical agitation of the waste. This pre-treatment step is then followed by a sieving operation. Therefore, due to size reduction, which is very effective in the paper and cardboard fractions, the content of these materials increases significantly in the material fraction for composting (Morvan *et al.*, 2002, 2003). In plants without rotary drums, there is also a sieving step, normally at a size higher than in the plants with rotary drums. In the MBT plants considered here, the sieve size was in the range 25-40 mm for plants with rotary drums, and 50-80 mm for plants without. However, in the latter, most of the paper and cardboard is excluded from the fraction for composting, as there is no size reduction step. It must be noted that paper has a significantly lower k than food waste and yard waste, as shown by the data of Komilis (2006) (table 6.1), and this means that paper content may have a significant effect on the k value of the waste.

Therefore, the rotary drums lead to (i) a size reduction of the waste, which can contribute to an increase in k by making more substrate available for the microbial community, but also (ii) increase the paper and cardboard contents in the material fraction for composting, which, inversely, should lower the k value. If this rationale is correct, one factor should tend to balance the other, as there are actually no big differences between the k values for the full-scale plants.

Table 6.1. k values estimated from the data of Komilis (2006) for a food waste recipe, yard waste and mixed paper.

Reference	Material	k (d^{-1})	R^2 of the model fit	$[BVS_o]$ (rel. VS)*	RT (d)
Komilis, 2006	Food waste recipe: milk + cooked pasta + hamburger + lettuce + raw potatoes + carrots in equal amounts (wet weight basis) + 10-15% (v/v) aluminium packing material	0.088	0.97	0.70	91
Komilis, 2006	Mixed paper corrected for a C/N = 25-30 shredded to 3-4 cm square pieces : MSW compost; 10:1 (dry weight basis) + 10-15% (v/v) aluminium packing material	0.022	0.96	0.33	198
Komilis, 2006	Yard waste - Grass clippings : leaves; 1,5:1 (dry basis) + 10-15% (v/v) aluminium packing material	0.070	0.97	0.58	69

*$[BVS_o]$ were estimated from the modelling procedure described in section 4.2.1 and 4.2.6.

6.4.2 k values from lab-scale studies

Unlike for the full-scale studies, k values from the lab-scale studies were observed to vary widely, even when similar types of composting materials were used. In addition, k values could reach much higher values than in the full-scale studies. This leads one to consider that:

- Not all the factors which significantly affect k were included in the model;
- A large margin exists for improvement of the efficiency in full-scale systems;
- Extrapolation from the lab- to the full scale can be misleading and should be made carefully.

These considerations will be discussed in detail in the next sections.

6.4.2.1 Factors which affect k

It was previously suggested (Haug, 1993; Mohee *et al.*, 1998; Hamelers, 2001, 2004) that the type of composting model used in this work, which corrects k for T, MC, $[O_2]$ and FAS, does not account for all the corrections that have to be made in order to convert k to a universal basis. The findings from this study corroborate these suggestions. It is likely that other factors that were not considered may play a significant effect on k. These "missed" factors may be the following:

- Particle size;
- Waste composition;
- Microbial populations in the waste (diversity and sizes);
- Spatial gradients of environmental, substrate and microbial conditions.

Each of these factors will be discussed in separate as follows.

Particle size

Particle size was certainly one source of variation between the corrected k values. Information about waste maximum particle size was not given in all studies, but analysis of the available information shows that this was very variable, especially in lab-scale studies. In some cases, particle size went up to 50 mm, in other cases it did not go above 10 mm.

Particle size patterns along the composting process must also be very variable, since factors such as the type of waste, the pre-treatment processes, the type of composting system or the operating conditions, should all influence the particle size variation throughout the process.

The influence of particle size on the composting rate has been poorly studied by the composting research community, mostly due to the complexity of the topic. In fact, although some authors have attempted to quantify and monitor particle size along the composting process, namely by sieving procedures (Tseng *et al.*, 1995; Aboulam *et al.*, 2006; Lornage *et al.*, 2007; Tosun *et al.*, 2008), there is no method available that has proven to accurately quantify this factor experimentally (Hamelers, 2001, 2004; Agnew & Leonard, 2003). However, this topic has already been an object of attention by some researchers.

Nakasaki *et al.* (1987) found that the reaction rate obtained for two sludges of different particle sizes was approximately proportional to the surface area of those sludges. These authors suggested that microorganisms responsible for the degradation process grow by forming colonies only on the macroscopic solid surfaces with sufficient free air space.

Haug (1993) analysed the influence of particle size on process kinetics, from a standpoint of oxygen diffusion into the particles. He concluded that particle thickness of the order of 1.0 cm would appear to present a large diffusion resistance that would tend to dominate process kinetics. Haug (1993) concluded: "*This leads to a rather complex picture of oxygen supply because diffusion transport and particle size should both be considered. Such a sophisticated model is beyond the present state of the art.*"

Probably the most complete study on the effect of particle size on the composting rate has been carried out by Hamelers (1993, 2001), where a deductive strategy was used, together with dimensional identifiability analysis, to study the kinetics of the composting process. With his mechanistic model, Hamelers concluded that particle size strongly affects composting rate.

The simulations of Hamelers (1993, 2001) and Tseng *et al.* (1995) predict that anaerobic conditions will occur within the interior of substrate particles greater than 0.25 mm in diameter, even with high oxygen concentrations in the gas phase surrounding the particles. Similarly, Kovács *et al.* (2007) conclude that only the outer 0.5-1 mm layer in sewage sludge can be considered as biodegrading actively in composting, due to oxygen diffusion

limitations. Nielsen & Berthelsen (2002) also obtain results that indicate that oxygen diffusion rate in the composting particles is very limiting for distances larger than 1 mm. Therefore, taking into account these findings and the information on particle sizes in the studies analysed here, when available, one is led to think that this must have been a significant limiting factor to process rate, in most of these studies.

Nevertheless, although smaller particle sizes led to faster composting rates in some situations (Nakasaki *et al.*, 1987; Hachicha *et al.*, 1992; Magalhães *et al.*, 1993), there were also studies where no effect was reported (Cathcart *et al.*, 1986; Hansen *et al.*, 1993) or where particle size reduction produced lower composting rates (Hamoda *et al.*, 1998; Bueno *et al.*, 2008). These studies show that particle size reduction is not advantageous in all situations. Using a theoretical approach, Hamelers & Richard (2001) get to similar conclusions. These authors concluded that size reduction as a feedstock preparation step leads to a higher density of solids, higher optimum dry matter content, and consequently a lower rate of biological activity, due to lack of moisture; size reduction leads to smaller primary particles, but due to enhanced compaction it results in larger secondary particles. Therefore, the same authors suggest that feedstock preparation should ideally adjust particle size to match the moisture levels and densities of each composting system under study.

Lastly, it should be mentioned that a correction factor for particle size was already included in a simulation model (Xi *et al.*, 2005; Qin *et al.*, 2007). This factor was considered to vary between 0 and 1, and its determination was empirical.

It is suggested that particle size is a major source of variation in between the k values studied here. It is also suggested that a standard material preparation procedure should be defined, namely regarding the particle size of the materials under study, together with a standard waste recipe (see next topic), in order to reduce the sources of variation in lab-scale studies.

Waste composition

Although we strived to find studies using similar composting materials to the ones studied in this work, there are still variations in composition. There are even variations in between the composition of the wastes studied experimentally in this work, especially between MBT2 waste and the other plants' wastes (section 5.2.1). Composting materials considered in the comparative analysis of the k values varied from MSW or biowaste as collected from the households to dog food, or food waste recipes.

Factors like nutrients balance, e.g., C/N ratio (Gray & Biddlestone, 1973; Jeris & Regan, 1973c; Kayhanian & Tchobanoglous, 1992; Nakasaki *et al.*, 1992a; Ekinci *et al.*, 2002; Díaz *et al.*, 2003) were normally accounted for and corrected, if necessary. Therefore, the main

source of variation must have been related to the biodegradability and availability of the component substrates in each case. For example, the paper content of the wastes was very variable (table 5.12), ranging from no paper at all (Richard, 1997; Namkoong *et al.*, 1999; Komilis, 2006; Briski *et al.*, 2007) to 12.5% of paper (Bari *et al.*, 2000) or possibly even higher in the MSW studies (Keener *et al.*, 1997; Hamoda *et al.*, 1998; Adani *et al.*, 2000). As mentioned previously, paper may contribute to the decrease of the k value of the waste (cf. table 6.1).

This is one of the reasons why it is imperative to adopt a standard waste recipe, as suggested by others (Schulze, 1960; Clark *et al.*, 1977; Palmisano *et al.*, 1993; Schwab *et al.*, 1994; Petiot & de Guardia, 2004; Mason, 2008c). This would enable the elimination of the waste composition variability factor when comparing studies from different authors, at a lab scale.

Composting modelling approaches have been attempted which take into account the composition of the waste, therefore trying to account for the differential biodegradabilities of the several waste components (Kaiser, 1996; de Guardia *et al.*, 2001; Tremier *et al.*, 2005; Komilis, 2006; Sole-Mauri *et al.*, 2007; Lin *et al.*, 2008a, 2008b). These models, however, generally require a substantial experimental effort, both in terms of validation and practical application, and have not been extensively adopted.

Microbiological populations in the waste

In this study, we did not attempt to control the composition of the microbial communities in the waste, and the diversity and abundance of the microbial communities in the different systems studied must have differed significantly. Factors like waste composition, handling of materials, local climate, the use of seeding materials, or even different composting process management are all possible causes of variability.

As for the composition of waste, composting models were developed which account for the sizes and types of the microbial populations, to a smaller or larger extent (Hamelers, 1993; Kaiser, 1996; Stombaugh & Nokes, 1996; Agamuthu *et al.*, 2000; de Guardia *et al.*, 2001; Zavala *et al.*, 2004b; Tremier *et al.*, 2005; Xi *et al.*, 2005; Qin *et al.*, 2007; Sole-Mauri *et al.*, 2007; Bongochgetsakul & Ishida, 2008; Lin *et al.*, 2008a, 2008b; Xi *et al.*, 2008; Yu *et al.*, 2009). These models, however, require a tremendous experimental effort for validation and practical application, sometimes out of the reach of the current experimental techniques. In addition, model parameters are often estimated from data on the literature. Consequently, these models have not been extensively adopted.

Gradients in the system

There are gradients along the waste matrix in composting systems/reactors, the extent of which depends on the characteristics of each system. These gradients can be related to environmental conditions, substrate composition, physical structure, and/or microbial community diversity and abundance. These heterogeneities in the composting matrix along the whole system may cause a differential process rate accordingly. Therefore, systems with frequent and efficient mechanical turning should have a greater potential to speed up the composting process, as heterogeneities can be kept to a minimum and it is thus easier to maintain all the composting material in conditions close to optimum levels. This was actually verified experimentally by Chang *et al.* (2006a, 2006b), which conducted lab composting trials with dog food and vegetable waste. These authors concluded that organic matter degradation was greatest in the trials with the highest agitation periods.

Furthermore, systems with large gradients are difficult to study, as they require extensive experimental monitoring for as many points in the system as possible. Otherwise, the measured conditions may not reflect the real conditions in the whole system, and significant deviations from reality, in terms of modelling outputs, can be obtained.

The existence of gradients can be coped with, from a modelling point of view, by accounting for spatial distribution in the models, instead of using a lumped parameter approach (Keener *et al.*, 1993; Van Lier *et al.*, 1994; Tseng *et al.*, 1995; Das & Keener, 1996, 1997; Stombaugh & Nokes, 1996; Vandergheynst *et al.*, 1997; Koenig & Bari, 1999; Bari & Koenig, 2000; Ekinci *et al.*, 2006; Qin *et al.*, 2007; Bongochgetsakul & Ishida, 2008; Yu *et al.*, 2009). In this way, the model considers differential rates in the different space units, if differential environmental conditions exist.

The fact that k value is relatively constant in full-scale MSW composting systems and that it is not in lab-scale systems is not completely unexpected. As mentioned earlier, the main source of variation in full-scale systems is in the waste pre-treatment, due to the inclusion or not of rotary drums. As discussed, when this step is included, there are two main alterations in the waste fraction for composting, but these should tend to balance each other.

In lab-scale systems, waste composition is easier to control than in full-scale systems, but this does not mean it is less variable. In fact, it is much more diverse. In addition, waste pre-treatment is also much more variable in lab-scale systems, which results in a large variation in particle sizes. At this scale, as the amounts of waste are much smaller than in full-scale systems, more attention can be paid to materials preparation, and it is possible to reach very small particle sizes.

Another reason may also be related to the size of the system. In lab-scale studies, the small size of the systems makes it much easier for the operator to make a better management of the composting process. Mixing thoroughly all the composting material is an uncomplicated task, and this operation can easily be repeated very frequently. These actions will eliminate heterogeneities in the system, and favour a complete colonisation of the material by the composting microbial population, which can contribute to an increase in k. In full-scale systems, this is much more difficult to achieve.

One last factor for the capability of lab-scale composting systems in achieving higher k values may be linked to the fact that, in this type of systems, it is much easier to maintain all the composting material in the operating environmental conditions. In full-scale systems, the much bigger amounts of composting materials involved favour heterogeneity in the environmental conditions, hence reducing the reaction rate. Furthermore, if this heterogeneity is missed during experimental data collection, also it may affect the value of the k estimate.

In conclusion, the small scale of the lab-scale studies makes it easy to pay a high level of attention to the system. If the system is well cared for, high k values can be achieved. However, it may also be the case that not much attention is paid to the system at this scale, which should be the reason for the low k values that are also observed at this scale.

6.4.2.2 Margin for improvement

The previous observations lead one to think that there is a big margin for improvement in the performance of real-scale systems. If the composting conditions in the high k lab studies can be reproduced at full scale, then a high k composting system can be produced.

However, this does not ensure *per se* good system performance at full-scale. In addition to the achievement of a high k system, optimised environmental conditions must be maintained in the process. If both these conditions are fulfilled, than a very high rate full-scale composting system can be achieved.

Implementation of such a full-scale system may be possible, provided the economics of such a system are acceptable.

6.4.2.3 Extrapolation from the lab-scale to full-scale

The composting research studies found in the bibliography are far more numerous at lab scale than at full scale. The higher costs, the smaller degree of control and the high labour inherent to full-scale composting studies (Hogan *et al.*, 1989; Petiot & de Guardia, 2004; Mason & Milke, 2005a) have promoted an increased choice for lab-scale studies, up to a point where full-scale systems have been somehow underestimated. The central aim when designing lab-

scale systems is to produce an apparatus in which field like behaviour can be simulated (Hogan *et al.*, 1989). However, this downscaling process *"is typically accompanied by a certain loss of the reality which is inherent at the full scale"* (Mason & Milke, 2005a).

Lab- or pilot-scale composting studies are often performed with the aim of producing data for the design of full-scale systems. Golueke (1977) (cited *in* Tollner *et al.* (1998)) is recognized as a pioneer in the use of this approach, which has been extensively used since (Haug, 1980, 1993; Cathcart *et al.*, 1986; Hansen *et al.*, 1993; Keener *et al.*, 1993, 1995, 1997, 2002, 2003, 2005; Das & Keener, 1996, 1997; Das *et al.*, 1998; Tollner *et al.*, 1998; Scholwin & Bidlingmaier, 2003). Even when the main objective of the work is not the optimization of the design or of the operation of full-scale systems, these are often important concerns (Whang & Meenaghan, 1980; Tseng *et al.*, 1995; Richard, 1997; Nielsen & Berthelsen, 2002; Hamelers, 2004; Chang *et al.*, 2005, 2006a; Chang & Hsu, 2008; Petric & Selimbasic, 2008; Yu *et al.*, 2009).

The use of lab-scale reactors to simulate full-scale composting systems was a subject of review and analysis by Petiot & Guardia (2004) and Mason & Milke (2005a, 2005b), especially from the standpoint of the heat balances, where deficiencies in the downscaling process were identified. These authors highlighted the importance of recreating the full-scale systems in the lab as faithfully as possible, when the aim is to extrapolate the lab-scale results to the full scale.

Findings from this work corroborate these conclusions and suggestions. It was observed that k values from full-scale systems and from lab-scale reactors, although corrected for T, MC, $[O_2]$ and FAS, can vary significantly. This is very likely to mean that factors such as particle size, waste composition, materials handling, turning operations, as well as the environmental conditions of the full-scale system, should be mimicked in the lab as faithfully as possible, at least until these factors can be fully included in the simulation models. Otherwise, k values in the lab systems may differ significantly from those in the full scale, up to a point where erroneous extrapolations are made. This may result in deficient full-scale system design or operational practices.

In addition, these results demonstrate the need for intensifying the research on full-scale systems. The usefulness of lab-scale studies is unarguable, but their performance in recreating full-scale systems should not only be, as mentioned, a subject of attention, in the sense that full-scale conditions should be recreated in the laboratory as faithfully as possible, but also a subject of control. Full-scale studies can act as an important control over lab-scale studies in this task, especially when these lab-scale studies aim at optimizing the design or the operation of full-scale systems.

7. CONCLUSIONS

The conclusions from this work are presented in this section, as follows.

Testing for the adequacy of the simulation model to describe the experimental data collected

- The simulation model proved to describe the experimental data from MBT1, MBT2 and MBT3 well. k (kinetic rate constants corrected for T, MC, $[O_2]$ and FAS) values were estimated at 0.063 d^{-1}, 0.043 d^{-1} and 0.082 d^{-1} and k' (uncorrected kinetic rate constants) at 0.013 d^{-1}, 0.019 d^{-1} and 0.039 d^{-1}, respectively;
- Simulation of the MBT4 data was less successful, most likely due to sampling errors associated with the VS measurements. k and k' estimates for this plant were considered to be affected by a considerable level of uncertainty.

Study of the effect of the model parameters in k estimation

- Sensitivity analysis showed that the behaviour of the four plants studied was similar, with respect of the response of k to changes in the simulation model parameters ($[BVS_o]$, T_{min}, T_{max}, T_{opt}, K_{O_2}, MC_{opt} and FAS_{opt});
- The sensitivity ratios for $[BVS_o]$, T_{max} and MC_{opt} were the highest, which means that these are the most influential parameters on k estimation;
- The least influential parameters on k estimation are T_{min}, K_{O_2} and FAS_{opt};
- Sensitivity ratios between 3 and 4 show that variations in certain model parameters amplify the k estimate variations by 3 to 4 times.

Diagnosis of operation performance and evaluation of the potential for optimization in the MBT plants

i) Diagnosis

- Process rate limitations were identified, and were found to be particularly significant in MBT1 and MBT2;
- The most limiting factors for the process rate varied according to process stage. Regarding the initial stage of the process, there was, in all plants, a limitation caused by low T and $[O_2]$ conditions. In the middle stages, T was a significantly limiting factor for composting rate in all the studied plants, but due to high T values. MC was also a significantly limiting factor in the middle process stages in MBT1 and MBT3, due to low MC values. In the final stages of the process, composting rate was significantly limited by the low MC levels in all plants, and T was still significantly limiting in MBT1 and MBT4, due to excessively high T;

- MBT4 is an isolated situation in this set of four plants, most likely because process time is much shorter, and the material turning frequency is much higher (every two days) than in the other plants. MBT4 performed best, in its time scale. It was also found that MBT3 performed much better than MBT1, which illustrates how the operation performance is important in a MBT plant, because the composting systems and MSW are similar in these two plants. The performance of plant MBT2 was in between MBT1 and MBT3;
- Total BVS degradation in the plants was estimated at 46% in 59.8 days for MBT1, 51% in 45.5 days for MBT2 and 84% in 61.5 days for MBT3. This data confirms the good operation performance in MBT3. For the reasons mentioned before, data on MBT4 was concluded to be affected by a considerable level of uncertainty;
- In sum, the three components of analysis (individual correction factors, F(TOT) and k', and VS degradation) proved to be complementary and provide an invaluable insight into the operation performance of the composting process in the plants.

ii) Potential for optimization

- A large margin for process management improvement was observed in some of the full-scale systems studied. Estimates on the increases in VS consumption produced by the application of the optimization measures were as high as 103%, 53%, 17% and 26% for MBT1, MBT2, MBT3 and MBT4, respectively;
- The environmental factors that produced *per se* the highest increase in VS consumption were MC for MBT1 and MBT3, and T for MBT2 and MBT4;
- The results of this analysis are workable in the field, normally in a relatively simple manner. By changing the aeration cycles or the ventilation capacity, water addition regimes, material turning regimes, pile size, or by the use of a bulking agent, depending on which are the objects of optimization, one can act upon the environmental conditions accounted for in the model (T, MC, [O2] and FAS).

iii) Global (diagnosis plus optimization) analysis

- It is important to have:
  - Well designed systems, which allow operation close to optimum conditions;
  - Good process managers in full-scale composting systems;
  - Monitoring programs for full-scale composting systems.

  Situations were identified here where poor process management compromises process performance, and hence the quality of the final compost and the impacts of the plant on the

environment and surrounding populations. In the overall, the profit that can be taken from the investment is compromised by poor process management practices;

- It is proposed that the procedures developed here for data collection and treatment are routinely applied to full-scale composting plants for operation performance evaluation and optimization. The connection between research and industry is certainly advantageous and must be strengthened. In addition, the practical implementation of these procedures is relatively simple. The methods involved are not difficult to execute and do not require complex or too expensive equipment. In some situations, at least part of the necessary equipment is already used in the plants. Furthermore, data collection can be carried out by the staff working in the plant, if proper training and monitoring are provided. Therefore, these procedures can be implemented by the plant operators.

Comparison of k estimates with k obtained from the literature

- k values from lab-scale studies varied widely. This corroborates previous suggestions (Haug, 1993; Mohee *et al.*, 1998; Hamelers, 2001, 2004) that the type of composting model used in this work, which corrects k for T, MC, $[O_2]$ and FAS, does not account for all the corrections that have to be made in order to convert k to a universal, comparable basis, in all these systems. It is likely that other factors may play a significant effect on k and were not accounted for. These "missed" factors may be amongst the following: particle size; waste composition; microbiological populations in the waste (species and sizes); and spatial gradients of environmental, substrate and microbiological conditions;
- k values from full-scale studies do not vary greatly, and k variation in the lab-scale systems is much wider, and can reach much higher values, than in full-scale systems. This may result from the higher variability in waste composition and waste pre-treatment procedures in the lab-scale systems, the ease in achieving a very good level of process management (thorough and frequent mixing of the material, etc) and in reducing heterogeneities at this scale;
- There is a big margin for improvement in the performance of real-scale systems. If the composting conditions yielding the high k values in the lab-studies could be reproduced at a full-scale, then a high k composting system would be achieved;
- Extrapolation of lab-scale results to full-scale systems can be misleading and should be made carefully, trying to recreate the full-scale system in the lab as faithfully as possible. Factors like particle size, waste composition, materials handling, turning operations, as well as the environmental conditions of the full-scale system, should be mimicked in the lab as thoroughly as possible;

- Although there is a great predominance of the number of lab-scale studies over full-scale studies in the composting bibliography, and although the former are of great importance, the findings from this work alert to the need of increasing the number of full-scale studies. These latter can act as an important control over lab-scale studies, especially when these lab-scale studies aim at optimizing the design or the operation of full-scale systems.

8. FUTURE WORK

The evaluation and optimization study performed for the full-scale MBT plants shows that the procedures developed here for data collection and treatment are promising for practical implementation. Further validation of the applicability of these procedures can be achieved with the follow up of the resulting optimization measures. The model is capable of predicting a variation in the VS degradation profile, as a result of a change in the environmental conditions, and it is important to verify in the future if the predicted VS profiles are in accordance with the results obtained in practice.

The definition of the optimized environmental conditions, necessary for the optimization analysis, is another aspect for future improvement. A higher support to the definition of these conditions would require the consideration of the energy balance of the process, which should be introduced in the model.

Comparison of the k estimates obtained in this work with those calculated from data in the bibliography suggest that other factors than those included in the model have a significant effect on composting rate. These factors may be, as suggested, particle size, waste composition, the microbial populations in the waste (species and sizes), and the existence of spatial gradients of environmental, substrate and microbiological conditions, which should be further studied.

The sampling and analysis procedure for VS determination should be further investigated in order to make it capable of producing more accurate and precise data than the one obtained here. When VS are to be used as a process monitoring parameter, good precision and accuracy is desirable for the results. Increasing the number of samples may be sufficient for this purpose.

If higher accuracy and precision is achieved on the VS determinations, then a two-time scale model should be tested for the description of the process kinetics.

The results obtained here also suggest that further work should be carried out on the composting rate dependence on those factors that were shown by the sensitivity analysis to strongly affect k, and that are not sufficiently studied, namely $[BVS_o]$, T_{max} and MC_{opt}. Regarding $[BVS_o]$ determination, it is important to develop a standardized procedure that provides information on the actual degradation that may be achieved in normal composting conditions. Concerning MC, special attention should be given to materials like MSW, which have significant contents of materials which do not absorb water, thus interfering with the MC results.

One assumption in the modelling approach used here is that the environmental correction factors (F(T), T(MC), F($[O_2]$) and F(FAS)) are independent from each other. Although this is

common practice in composting modelling, there are results in the bibliography which indicate that this may not be true (section 2.2.7). This research field has not been properly explored and should be further studied in the future.

Lastly, modelling should continue to be explored as a tool to reach further advances in the understanding of the composting process. Inductive modelling (section 2.1.6) may be useful in getting a deeper insight into the meaning of experimental observations. However, deductive modelling (section 2.1.6), being a relatively unexplored field in this area, may open the way for a new understanding and perspective of the composting process. This work was initiated by Hamelers (1993, 2001, 2004), and efforts should be gathered in order to give it continuity.

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APPENDIX A

This appendix presents the individual experimental results obtained in this work for the four plants studied. These results refer to the T, MC, [O_2], BD, FAS and VS content measurements, which were presented graphically in figures 5.1-5.4.

A.1 MBT1

Table A.1. MBT1 - Temperature measurements (ºC). (To be continued)

			Zone									
Day	Point	Depth (m)	1	2	3	4	5	6	7	8	9	10
1	1	0.5		41.0	45.7	57.8	65.2	65.1	60.5	69.2	61.4	51.7
		1.0		40.5	47.8	48.6	68.8	63.5	74.1	68.2	55.1	60.6
	2	0.5		40.4	47.6	61.2	64.9	63.6	66.0	70.2	48.1	50.0
		1.0		40.7	46.5	52.6	65.4	65.5	65.1	70.1	56.2	57.9
	3	0.5		40.4	50.4	62.2	65.6	56.2	60.3	63.5	35.9	48.8
		1.0		40.5	47.9	63.5	61.2	45.6	50.0	60.2	51.9	54.6
	4	0.5		41.9	49.5	62.9	63.3	62.3	64.4	63.6	42.8	64.4
		1.0		41.1	53.5	65.9	65.9	61.6	65.6	60.8	39.8	55.9
	5	0.5		42.3	51.1	63.8	63.0	63.3	65.1	65.3	43.8	64.1
		1.0		42.0	51.5	65.8	70.4	71.5	74.8	65.5	40.6	62.6
	6	0.5		43.6	53.6	65.2	66.5	71.0	69.1	62.6	42.6	51.2
		1.0		44.4	54.0	67.7	71.5	78.7	74.0	59.0	39.3	63.4
2	1	0.5	37.9	47.4	54.1	56.1	57.1		61.9	61.7	54.0	62.8
		1.0	35.0	44.2	51.4	52.7	69.0		60.0	64.8	66.5	68.9
	2	0.5	38.1	45.0	54.1	59.5	58.4		63.5	62.9	54.5	65.3
		1.0	33.6	44.5	49.0	54.6	67.5		59.9	63.5	65.1	67.7
	3	0.5	38.5	45.7	56.4	61.4	53.8		69.2	66.7	57.5	67.1
		1.0	36.1	45.1	50.3	63.1	60.2		64.2	64.0	61.5	69.7
	4	0.5	38.9	46.8	57.2	60.5	51.2		61.9	59.5	64.3	61.6
		1.0	37.8	45.7	60.3	61.9	66.7		67.2	65.5	63.1	68.9
	5	0.5	39.7	48.0	55.6	60.3	57.1		57.4	58.0	63.0	64.5
		1.0	35.6	45.8	58.6	61.9	67.3		62.1	66.0	67.4	64.3
	6	0.5	42.9	50.7	55.2	61.0	56.6		59.8	56.9	63.0	65.0
		1.0	37.1	48.0	59.9	64.2	68.6		64.0	65.6	66.2	59.3
3	1	0.5	39.6		44.6	52.9	55.4	66.5	76.1	71.2	70.3	70.0
		1.0	39.2		45.5	52.2	54.1	63.9	74.4	73.7	72.4	71.0
	2	0.5	37.9		45.8	51.5	57.1	63.9	73.3	72.5	72.8	71.8
		1.0	37.4		45.0	49.2	53.2	62.8	73.9	74.7	72.7	72.1
	3	0.5	24.5		48.4	53.2	63.1	65.2	71.2	72.5	72.2	66.0
		1.0	38.5		45.7	49.5	59.8	49.2	66.8	61.0	74.2	62.0
	4	0.5	22.7		48.8	55.8	67.6	67.9	71.5	76.6	64.0	68.0
		1.0	39.5		47.7	54.5	65.2	69.0	74.1	74.6	74.5	70.2
	5	0.5	23.6		49.1	56.6	61.4	69.1	63.5	73.0	71.5	71.3
		1.0	40.5		46.8	55.2	65.1	68.7	70.8	74.0	71.9	67.3
	6	0.5	27.0		52.8	57.0	63.8	72.0	67.7	74.6	73.0	66.7
		1.0	42.2		48.3	55.0	63.6	70.5	73.2	74.0	74.2	52.3
4	1	0.5		45.0	52.5	58.2	64.3	72.7	78.0	75.9	76.6	76.1
		1.0		40.3	56.6	57.7	65.6	73.2	75.3	75.2	73.1	69.9
	2	0.5		43.4	49.6	55.4	59.9	74.3	76.1	74.8	74.8	74.4
		1.0		39.3	50.1	55.1	61.9	73.9	75.4	74.7	72.5	72.5
	3	0.5		42.1	50.4	59.9	67.2	72.6	75.0	72.5	72.7	74.3
		1.0		39.9	49.6	59.0	70.3	73.6	70.6	65.9	73.4	72.1
	4	0.5		41.8	46.2	59.7	71.4	73.3	75.2	74.8	72.8	70.4
		1.0		40.9	56.7	64.2	61.9	75.2	74.7	71.9	73.7	65.1

Table A.1. MBT1 - Temperature measurements (ºC). (Continuation)

			Zone									
Day	Point	Depth (m)	1	2	3	4	5	6	7	8	9	10
4	5	0.5		42.8	52.0	65.7	73.0	72.1	70.8	74.0	72.6	69.7
		1.0		43.7	61.3	70.3	67.6	75.5	77.2	74.6	72.8	64.7
	6	0.5		40.1	58.7	70.6	72.1	80.0	74.8	74.1	73.4	71.3
		1.0		39.9	64.9	75.5	71.1	80.6	76.5	76.3	74.4	61.7
5	1	0.5		44.3	52.7	62.0	58.6	69.5	79.9	71.0	72.5	74.1
		1.0		44.2	57.4	62.0	63.0	74.1	74.9	74.3	72.5	66.2
	2	0.5		43.2	53.3	58.1	60.0	71.8	75.4	72.5	72.1	73.4
		1.0		42.6	55.3	54.3	60.3	77.0	71.9	73.0	73.0	67.6
	3	0.5		47.0	51.1	57.9	59.2	71.6	72.0	73.3	72.6	71.8
		1.0		42.9	51.6	61.5	64.0	68.0	61.3	72.1	69.8	67.9
	4	0.5		46.9	55.9	62.1	64.8	73.0	72.3	74.8	71.4	72.0
		1.0		43.1	61.1	68.3	69.6	72.5	69.1	71.9	68.8	71.6
	5	0.5		45.6	62.0	66.9	71.5	78.1	72.0	70.1	72.6	71.8
		1.0		41.5	63.6	65.7	73.9	79.1	71.7	75.0	70.6	66.5
	6	0.5		45.0	65.3	62.5	72.0	82.0	70.4	68.3	73.8	70.4
		1.0		42.8	67.0	65.9	75.4	83.1	72.0	73.7	72.8	62.3
6	1	0.5		42.6	54.5	62.0	68.2	71.8	79.4	74.8	76.2	69.0
		1.0		41.9	60.2	60.1	73.6	68.8	75.7	70.8	71.5	66.4
	2	0.5		46.0	54.8	58.9	73.9	70.7	74.9	75.1	75.9	70.8
		1.0		42.8	59.3	52.9	77.2	71.5	63.0	72.6	73.2	67.8
	3	0.5		46.7	53.2	60.5	72.3	71.2	68.9	75.1	74.6	72.0
		1.0		42.4	53.1	61.9	63.8	66.0	64.6	71.7	71.7	71.4
	4	0.5		46.3	58.0	62.0	63.0	69.8	70.8	74.7	71.0	71.6
		1.0		42.5	61.0	66.9	59.8	68.1	68.2	71.7	66.3	65.7
	5	0.5		46.0	62.4	64.7	67.0	70.2	74.8	76.8	68.3	70.0
		1.0		43.0	63.8	67.6	61.0	76.0	71.6	74.8	66.0	64.5
	6	0.5		46.0	67.0	68.0	67.6	83.0	76.1	78.6	68.3	69.8
		1.0		45.0	67.0	70.0	64.7	84.9	76.8	75.5	64.7	60.5
7	1	0.5	26.5	41.6	63.0	61.8	72.8	66.4	60.0	68.1	61.0	51.6
		1.0	28.1	47.8	64.4	62.7	77.2	65.2	73.9	67.0	56.0	60.7
	2	0.5	29.5	44.9	61.8	58.6	69.7	73.1	62.5	71.0	48.7	49.8
		1.0	31.2	45.7	62.8	58.1	69.5	64.5	66.0	72.0	55.9	56.8
	3	0.5	29.1	46.5	60.0	61.0	68.9	74.3	61.9	62.3	36.2	47.8
		1.0	30.8	45.5	57.4	64.5	73.8	71.0	55.2	59.9	51.6	52.9
	4	0.5	30.3	46.8	59.0	65.4	70.0	71.9	67.0	61.2	41.9	63.8
		1.0	38.7	44.1	61.0	66.0	75.5	68.4	65.0	60.9	39.7	55.7
	5	0.5	31.4	46.5	60.0	65.5	70.3	69.7	64.3	64.9	44.1	60.2
		1.0	39.8	44.0	65.3	69.5	72.1	67.3	70.1	64.2	40.1	51.9
	6	0.5	33.0	46.6	63.0	68.0	69.0	69.2	68.7	62.6	44.8	63.3
		1.0	38.5	46.9	68.2	72.0	73.4	71.3	73.0	59.0	39.9	63.4
8	1	0.5	20.0	39.9	59.3	64.0	67.3	78.7	80.0	70.5	72.8	70.1
		1.0	38.3	46.4	66.0	64.3	74.4	79.1	74.2	71.9	70.6	65.9
	2	0.5	38.5	47.7	62.5	61.2	70.8	78.2	75.1	72.4	74.4	68.3
		1.0	39.1	46.0	66.1	59.7	68.6	74.6	71.2	72.1	73.3	65.6
	3	0.5	37.3	50.0	60.2	63.8	71.0	72.6	70.1	73.7	72.7	68.3
		1.0	40.5	46.6	60.4	68.2	74.1	61.3	62.1	72.6	69.9	65.6
	4	0.5	32.0	48.2	63.4	70.7	70.5	71.2	70.1	72.5	70.6	70.2
		1.0	41.8	45.5	65.9	75.1	65.6	68.8	66.3	71.3	68.4	69.5
	5	0.5	24.6	48.1	67.1	71.0	72.5	78.0	72.7	71.7	69.7	70.0
		1.0	41.8	45.4	69.5	77.3	72.9	78.6	72.3	71.4	67.9	69.0
	6	0.5	20.1	48.4	70.1	67.5	73.6	79.1	76.2	72.8	69.5	68.2
		1.0	40.5	49.7	69.6	78.0	74.4	82.5	71.9	73.0	69.7	64.4

Table A.1. MBT1 - Temperature measurements (ºC). (Continuation)

			Zone									
Day	Point	Depth (m)	1	2	3	4	5	6	7	8	9	10
9	1	0.5	38.2	47.2	62.6	64.7	74.8	71.0		63.4	58.9	58.9
		1.0	41.8	45.7	69.1	66.2	74.3	76.0		60.8	59.9	60.5
	2	0.5	40.0	52.0	64.7	61.6	72.2	73.0		61.1	58.7	60.0
		1.0	41.9	45.0	65.5	67.9	71.6	75.6		61.8	60.1	61.4
	3	0.5	42.6	55.0	61.3	64.0	70.0	73.1		59.8	58.4	60.7
		1.0	42.1	48.0	57.6	72.1	74.5	69.0		58.9	58.6	61.6
	4	0.5	32.1	53.2	54.3	72.0	72.5	70.5		58.5	58.1	60.5
		1.0	31.8	47.1	69.1	74.2	76.2	69.8		59.1	58.9	61.6
	5	0.5	29.3	50.1	69.0	71.0	71.4	68.2		57.9	57.9	60.4
		1.0	25.5	47.1	70.6	78.0	73.0	69.8		58.8	58.8	61.0
	6	0.5	27.6	49.5	70.0	74.4	70.6	67.0		58.3	58.3	61.2
		1.0	25.9	51.9	69.8	79.4	79.5	66.7		61.0	61.0	59.6
10	1	0.5	40.3	48.8		48.0	56.8	54.4	60.5	66.1	68.4	65.1
		1.0	42.7	46.6		47.5	53.6	59.0	67.0	67.3	71.0	67.0
	2	0.5	46.0	51.1		50.1	55.4	58.0	64.5	64.6	67.9	66.0
		1.0	43.7	47.9		51.7	52.0	61.2	69.2	68.8	70.0	63.6
	3	0.5	45.0	51.9		47.6	54.4	60.2	67.8	67.7	70.4	64.6
		1.0	41.4	47.0		48.5	54.1	61.5	64.0	67.1	69.5	63.9
	4	0.5	42.6	52.2		50.0	51.6	66.0	69.0	66.3	69.1	61.5
		1.0	35.2	47.3		53.1	52.7	66.3	55.1	71.5	67.5	65.1
	5	0.5	40.7	50.0		55.1	55.8	59.7	53.5	66.2	69.1	62.9
		1.0	33.8	46.5		58.9	57.3	60.8	52.3	73.1	64.8	61.8
	6	0.5	40.3	52.5		58.4	56.9	61.9	68.0	67.7	69.0	65.0
		1.0	34.0	49.1		57.5	54.4	61.1	62.1	73.1	64.7	59.0
Mean			*35.7*	*45.4*	*57.4*	*61.8*	*66.0*	*69.8*	*68.8*	*68.6*	*64.2*	*64.7*
SD			*6.4*	*3.4*	*7.3*	*7.2*	*6.9*	*7.0*	*6.4*	*5.7*	*10.7*	*6.2*

Table A.2. MBT1 - Moisture content determinations (%, wet matter basis).

		Zone									
Sample	Replicate	1	2	3	4	5	6	7	8	9	10
1	1	47.2	47.0	40.7	37.7	37.1	37.3	35.4	27.4	32.3	19.2
	2	46.6	49.0	52.4	40.7	36.4	34.6	32.7	26.2	32.4	19.5
2	1	51.1	49.0	46.3	41.8	38.4	38.3	38.1	33.8	28.1	19.3
	2	51.0	49.1	47.2	41.5	41.3	35.4	40.7	36.4	31.5	20.0
3	1	48.3	51.0	49.5	44.4	41.4	39.1	36.1	31.7	31.7	35.0
	2	45.0	44.9	45.2	45.7	41.1	37.9	35.6	31.3	29.5	35.8
4	1	48.5	50.9	43.5	28.2	30.0	29.8	28.4	22.4	31.1	27.5
	2	48.8	52.4	48.1	28.4	28.7	31.2	30.2	20.3	34.6	29.0
5	1	44.9	54.8	46.5	26.5	16.0	27.8	17.1	14.8	21.3	16.4
	2	47.8	51.4	48.0	28.9	16.4	29.7	23.9	14.2	19.0	18.2
Mean		*47.9*	*50.0*	*46.7*	*36.4*	*32.7*	*34.1*	*31.8*	*25.8*	*29.2*	*24.0*
SD		*2.1*	*2.8*	*3.2*	*7.6*	*9.7*	*4.2*	*7.1*	*7.8*	*5.1*	*7.2*

Table A.3. MBT1 - Oxygen concentration measurements (%, v/v). (To be continued)

		Zone									
Day	Point	1	2	3	4	5	6	7	8	9	10
1	1		18.0	14.6	2.4	3.1	12.5	16.0	16.4	12.5	18.3
	2		17.8	12.2	2.2	5.4	11.3	14.4	17.8	11.7	18.4
	3		0.1	16.4	2.4	5.6	19.2	15.7	20.3	17.4	20.1
	4		6.0	16.9	9.5	10.5	13.0	17.2	18.5	19.0	11.3
	5		5.4	16.8	0.4	5.5	6.8	15.4	14.4	16.4	5.5
	6		6.0	17.9	1.5	6.0	6.0	7.3	13.7	17.6	0.2
2	1	3.5	0.1	2.6	1.6		12.5	16.0	16.4	12.7	18.3
	2	4.0	2.0	4.6	10.4		11.5	14.4	17.6	11.8	18.4
	3	6.1	3.2	1.6	7.6		19.2	14.9	20.1	17.6	20.0
	4	3.2	0.3	11.2	10.1		13.0	16.9	18.6	19.1	11.3
	5	0.1	0.4	12.4	10.6		6.6	15.1	14.4	16.6	5.3
	6	0.1	0.3	11.6	10.2		6.0	7.2	13.7	17.5	0.2
3	1		7.9	15.1	10.9	1.1	14.7	12.8	12.6	6.2	14.2
	2		4.8	6.5	0.9	2.1	14.0	10.7	11.0	5.9	13.8
	3		4.0	13.8	6.3	14.5	14.7	13.7	12.9	4.9	12.5
	4		1.9	8.5	5.8	18.9	12.0	14.8	14.1	12.6	0.4
	5		11.8	10.7	0.1	14.7	13.9	13.1	13.1	12.5	4.0
	6		10.3	10.3	4.1	14.5	7.2	13.1	13.5	13.0	1.1
4	1		0.0	13.4	12.4	9.5	8.9	9.7	14.2	15.6	16.8
	2		0.0	0.1	2.3	1.6	5.5	9.2	11.8	15.7	16.3
	3		0.0	10.6	10.4	5.8	9.1	17.0	15.3	15.2	14.3
	4		0.0	13.1	13.6	14.8	8.6	18.1	15.5	14.0	0.1
	5		0.1	15.9	11.4	15.7	3.9	13.1	14.8	14.9	0.6
	6		0.0	16.7	4.3	9.1	4.5	13.5	15.4	15.5	0.2
5	1		0.0	6.3	2.4	1.2	10.2	5.7	15.2	15.9	
	2		0.0	1.8	0.2	0.6	10.2	5.0	13.7	16.1	
	3		0.0	0.0	3.3	10.2	14.6	4.3	14.4	16.4	
	4		0.1	3.2	7.4	13.5	10.9	4.8	15.2	17.8	
	5		0.0	10.2	4.7	11.9	8.0	4.8	15.2	16.0	
	6		0.0	13.9	3.9	10.7	5.6	4.3	15.8	16.3	
6	1		0.2	9.5	1.0	1.9	11.3	11.5	14.2	15.0	
	2		0.0	9.2	0.4	1.2	10.9	12.9	13.0	13.6	
	3		0.0	1.5	2.0	6.2	15.1	14.2	13.0	14.8	
	4		0.0	4.3	3.2	10.8	12.0	14.1	15.4	15.6	
	5		0.0	10.6	1.5	10.0	9.1	13.1	15.4	16.1	
	6		0.0	3.7	0.7	13.7	7.6	13.0	14.1	15.3	
7	1	0.1	0.0	11.1	3.0	5.8	14.0	13.1	15.3	15.9	17.6
	2	0.1	0.0	5.4	1.1	7.0	15.1	13.7	14.8	17.1	16.1
	3	0.2	0.0	1.3	3.6	8.0	15.7	13.8	14.7	15.4	16.4
	4	0.0	1.3	6.2	4.5	16.1	13.6	14.9	14.7	14.5	0.3
	5	0.0	0.0	7.7	5.5	15.1	11.5	12.6	15.0	15.8	0.5
	6	0.0	0.0	3.1	6.6	16.0	10.2	12.5	15.1	15.5	0.4
8	1	0.0	0.1	9.3	0.0	1.6	7.9	12.9	15.3	16.2	16.4
	2	0.0	0.1	3.7	0.0	5.2	13.3	14.9	14.1	16.4	16.9
	3	0.0	1.2	0.8	8.6	5.2	16.1	15.7	15.1	16.5	16.8
	4	0.0	0.0	7.6	7.5	16.0	13.1	14.8	17.1	16.9	10.2
	5	0.0	0.0	15.9	3.5	13.2	9.7	14.1	15.2	16.8	0.3
	6	0.0	0.4	16.8	0.9	12.8	7.0	14.1	16.5	16.3	0.1

Table A.3. MBT1 - Oxygen concentration measurements (%, v/v). (Continuation)

		Zone									
Day	Point	1	2	3	4	5	6	7	8	9	10
9	1	4.3	1.3	12.6	1.2	2.3		13.6	13.6	12.4	12.7
	2	0.1	0.0	10.2	0.2	1.8		17.9	12.1	14.3	11.6
	3	0.0	0.1	3.3	4.4	6.3		19.4	14.5	12.0	12.9
	4	0.0	0.0	10.4	4.4	15.6		15.9	12.2	7.3	0.0
	5	0.0	0.2	11.4	5.6	17.8		8.1	8.0	12.4	0.0
	6	0.1	0.1	9.8		17.4		3.6	11.5	8.4	3.2
10	1	0.2		11.8	10.0	1.8	14.4	12.0	10.0	14.2	12.7
	2	0.1		5.6	5.4	5.0	19.0	17.1	12.0	13.1	14.2
	3	0.0		15.1	11.4	7.9	19.4	18.3	15.1	13.3	14.1
	4	0.0		14.5	7.5	0.3	19.0	17.1	14.0	12.0	9.7
	5	0.0		12.6	5.8	6.2	14.0	16.4	12.1	11.7	1.2
	6	0.0		12.9	2.6	0.3	15.4	8.8	14.9	11.5	0.5
Mean		*0.7*	*2.0*	*9.4*	*4.8*	*8.4*	*11.6*	*12.9*	*14.6*	*14.3*	*9.3*
SD		*1.6*	*4.1*	*5.1*	*3.8*	*5.6*	*4.0*	*4.0*	*2.2*	*3.1*	*7.4*

Table A.4. MBT1 - Total bulk density determinations (g/cm^3, wet matter basis).

	Zone									
Sample	1	2	3	4	5	6	7	8	9	10
1	0.88	0.79	0.74	0.67	0.72	0.68	0.63	0.60	0.64	0.57
2	0.89	0.82	0.76	0.73	0.74	0.75	0.69	0.69	0.72	0.57
3	0.88	0.74	0.81	0.77	0.75	0.71	0.69	0.68	0.69	0.64
4	0.86	0.81	0.77	0.69	0.58	0.60	0.62	0.58	0.68	0.56
5	0.87	0.81	0.84	0.59	0.49	0.55	0.44	0.45	0.56	0.50
Mean	*0.88*	*0.79*	*0.78*	*0.69*	*0.65*	*0.66*	*0.61*	*0.60*	*0.65*	*0.57*
SD	*0.01*	*0.03*	*0.04*	*0.07*	*0.12*	*0.08*	*0.10*	*0.10*	*0.06*	*0.05*

Table A.5. MBT1 - Free air space values (fractional) (calculated as explained in section 4.1.7).

	Zone									
Sample	1	2	3	4	5	6	7	8	9	10
1	0.34	0.41	0.45	0.50	0.47	0.50	0.53	0.56	0.53	0.58
2	0.34	0.39	0.43	0.46	0.46	0.45	0.50	0.49	0.47	0.58
3	0.35	0.45	0.40	0.43	0.45	0.48	0.49	0.50	0.50	0.53
4	0.36	0.40	0.43	0.49	0.58	0.56	0.54	0.57	0.50	0.59
5	0.35	0.40	0.37	0.56	0.64	0.59	0.68	0.67	0.59	0.63
Mean	*0.35*	*0.41*	*0.42*	*0.49*	*0.52*	*0.52*	*0.55*	*0.56*	*0.52*	*0.58*
SD	*0.01*	*0.02*	*0.03*	*0.05*	*0.09*	*0.06*	*0.07*	*0.07*	*0.05*	*0.04*

Table A.6. MBT1 - Volatile solids content determinations (%, dry matter basis).

		Zone									
Sample	Replicate	1	2	3	4	5	6	7	8	9	10
1	1	39.7	48.5	50.6	50.8	41.2	47.6	45.7	37.8	44.3	40.7
	2	38.3	47.1	40.1	49.4	37.2	45.4	41.6	35.2	41.5	36.5
2	1	45.7	41.8	51.8	44.1	46.1	43.5	42.8	32.9	38.6	37.9
	2	45.1	44.3	38.0	40.6	48.1	37.4	43.6	41.7	45.0	38.9
3	1	56.9	51.9	45.2	42.1	44.3	42.2	39.5	35.8	41.7	42.5
	2	46.9	39.7	37.3	45.9	41.5	38.7	38.9	35.7	38.4	41.6
4	1	56.8	47.5	43.5	37.7	35.3	41.9	34.7	36.2	39.8	38.7
	2	55.7	53.7	51.5	41.4	38.9	42.1	36.6	36.0	43.6	39.3
5	1	42.1	45.1	42.7	44.4	36.1	36.6	40.9	44.2	40.2	34.5
	2	48.8	52.0	46.4	45.3	36.3	37.7	44.1	39.6	32.5	37.7
Mean		*47.6*	*47.2*	*44.7*	*44.2*	*40.5*	*41.3*	*40.8*	*37.5*	*40.6*	*38.8*
SD		*6.9*	*4.6*	*5.4*	*4.0*	*4.5*	*3.7*	*3.5*	*3.4*	*3.6*	*2.4*

A.2 MBT2

Table A.7. MBT2 - Temperature measurements (ºC). All measurements made at the depth of 1.0 meter.

		Zone						
Day	Point	1	2	3	4	5	6	7
1	1	32.7	55.6	69.1	70.7	78.5	55.3	49.2
	2	41.1	72.3	54.3	78.6	76.5	60.2	37.2
	3	32.5	68.9	51.5	59.1	74.9	50.1	49.9
	4	42.2	63.5	49.2	35.8	65.2	47.0	39.8
	5	44.2	68.3	65.8	32.2	65.4	39.2	39.0
	6	43.7	70.5	66.2	69.1	56.5	42.1	57.4
	7	32.7	49.6	59.2	64.7	63.8	46.4	53.9
	8	41.0	51.4	62.1	54.8	76.1	40.7	65.7
	9	39.0	47.9	64.2	67.0	77.9	49.4	66.3
	10	40.5	63.1	73.7	67.5	70.5	50.8	56.7
2	1	34.6	74.6	58.4	66.9	79.3	67.8	29.0
	2	38.0	47.9	50.1	62.1	64.0	70.0	35.1
	3	41.4	46.4	52.4	31.7	56.0	50.8	51.7
	4	41.5	65.6	58.0	73.2	79.0	54.4	40.4
	5	42.8	45.6	58.8	56.6	76.1	43.8	37.1
	6	37.9	46.7	65.8	68.9	61.2	41.6	55.0
3	1	38.7	74.8	59.1	70.5	80.8	70.6	64.5
	2	30.1	47.8	51.6	55.0	68.4	63.2	40.5
	3	33.6	48.2	55.6	71.1	56.7	46.7	48.8
	4	43.6	57.2	61.1	31.4	60.4	43.8	55.5
	5	41.3	46.4	59.5	69.4	79.2	48.2	41.2
	6	38.0	54.8	61.3	75.4	74.6	54.2	68.9
Mean		*38.7*	*57.6*	*59.4*	*60.5*	*70.0*	*51.7*	*49.2*
SD		*4.2*	*10.6*	*6.4*	*14.8*	*8.5*	*9.5*	*11.4*

Table A.8. MBT2 - Moisture content determinations (%, wet matter basis).

		Zone						
Sample	Replicate	1	2	3	4	5	6	7
1	1	58.0	54.4	51.7	46.0	49.9	40.2	41.5
	2	57.8	54.2	51.1	46.1	48.5	42.0	42.2
2	1	56.6	51.4	52.1	48.9	46.8	44.3	43.6
	2	56.8	53.1	52.2	47.8	46.8	44.5	43.2
3	1	57.2	51.8	52.5	49.4	41.2	48.7	44.0
	2	57.7		53.5	48.7	43.7	50.6	44.4
Mean		*57.4*	*53.0*	*52.2*	*47.8*	*46.2*	*45.1*	*43.1*
SD		*0.6*	*1.4*	*0.8*	*1.5*	*3.2*	*3.9*	*1.1*

Table A.9. MBT2 - Oxygen concentration measurements (%, v/v).

		Zone						
Day	Point	1	2	3	4	5	6	7
1	1	0.1	4.5	0.8	16.3	2.2	14.9	20.5
	2	0.0	7.6	3.0	2.7	0.3	16.1	20.4
	3	0.0	8.7	0.9	1.9	5.3	18.9	20.4
	4	0.1	5.7	8.2	18.3	0.8	20.3	20.1
	5	0.0	1.4	1.8	19.0	4.9	20.2	20.3
	6	0.0	5.2	4.0	2.3			20.2
	7	0.0	0.1	0.5	6.8			19.3
	8	0.0	5.6	0.8	11.2			20.1
	9	0.1	0.9	0.7	9.3			20.1
	10	5.8	1.5	0.3	12.6			19.9
2	1	0.0	0.4	0.0	12.3	10.7	15.0	19.4
	2	0.0	2.5	1.5	7.8	0.3	13.5	20.0
	3	0.0	0.0	1.2	4.5	2.5	14.4	17.6
	4	0.0	1.6	3.0	16.7	5.7	20.0	20.0
	5	0.0	0.5	1.4	19.4	6.4	19.2	20.3
	6	0.0	2.4	0.9	6.6			20.1
	7				11.6			
	8				13.2			
	9				10.3			
	10				11.2			
3	1	0.0	3.1	13.4	11.7	17.5	15.0	20.4
	2	0.0	0.6	1.9	12.4	5.0	16.9	20.3
	3	0.0	0.5	2.9	20.7	5.2	20.4	19.3
	4	0.0	4.3	4.6	12.0	1.7	17.7	20.3
	5	0.0	2.8	4.8	8.9	13.9	20.2	20.3
	6	0.0	4.9	6.0	12.7			20.3
Mean		*0.3*	*2.9*	*2.8*	*11.2*	*5.5*	*17.5*	*20.0*
SD		*1.2*	*2.5*	*3.1*	*5.2*	*5.0*	*2.5*	*0.6*

Table A.10. MBT2 - Total bulk density determinations (g/cm^3, wet matter basis).

	Zone						
Sample	1	2	3	4	5	6	7
1	0.81	0.71	0.68	0.67	0.71	0.66	0.66
2	0.81	0.73	0.64	0.65	0.68	0.67	0.60
3	0.75	0.70	0.68	0.66	0.65	0.67	0.60
Mean	*0.79*	*0.71*	*0.67*	*0.66*	*0.68*	*0.67*	*0.62*
SD	*0.03*	*0.01*	*0.02*	*0.01*	*0.03*	*0.004*	*0.03*

Table A.11. MBT2 - Free air space values (fractional) (calculated as explained in section 4.1.7).

	Zone						
Sample	1	2	3	4	5	6	7
1	0.34	0.44	0.46	0.49	0.46	0.51	0.51
2	0.34	0.43	0.50	0.50	0.49	0.50	0.56
3	0.39	0.45	0.47	0.50	0.51	0.50	0.56
Mean	*0.36*	*0.44*	*0.48*	*0.50*	*0.49*	*0.50*	*0.54*
SD	*0.03*	*0.01*	*0.02*	*0.01*	*0.02*	*0.003*	*0.02*

Table A.12. MBT2 - Volatile solids content determinations (%, dry matter basis).

		Zone						
Sample	Replicate	1	2	3	4	5	6	7
1	1	70.2	70.8	63.0	62.6	62.2	60.7	56.9
	2	68.9	63.4	63.1	60.4	61.3	59.6	56.4
2	1	68.8	60.6	64.5	63.8	61.2	58.3	58.3
	2	69.5	71.1	63.1	60.9	62.4	61.4	57.2
3	1	75.3	61.1	63.3	58.1	59.1	59.2	59.5
	2	70.0		66.3	56.6	61.3	57.5	58.1
Mean		*70.4*	*65.4*	*63.9*	*60.4*	*61.2*	*59.4*	*57.7*
SD		*2.4*	*5.2*	*1.3*	*2.7*	*1.2*	*1.4*	*1.1*

A.3 MBT3

Table A.13. MBT3 - Temperature measurements (ºC).

			Zone									
Day	Point	Depth (m)	1	2	3	4	5	6	7	8	9	10
1	1	0.5	50.0	47.6	60.6	60.4	67.5	60.1	73.0	67.0	70.6	53.8
		1.0	40.8	44.2	58.3	57.9	39.2	56.1	64.9	72.5	65.5	37.0
	2	0.5	29.1	50.2	62.0	64.3	66.7	59.5	72.2	70.0	70.5	52.6
		1.0	43.9	50.5	60.5	65.8	58.5	60.5	70.3	63.4	62.5	41.5
	3	0.5	30.3	36.9	62.9	63.4	67.3	58.5	72.5	67.4	70.5	51.3
		1.0	43.2	39.3	59.9	66.1	64.8	59.7	67.7	61.6	60.1	43.4
	4	0.5	29.4	50.3	58.2	64.0	64.5	58.6	70.1	65.5	67.2	51.1
		1.0	37.1	54.1	53.9	62.1	61.7	58.3	61.0	56.0	57.2	46.7
	5	0.5	35.0	43.9	60.4	66.3	63.6	65.7	70.0	65.3	65.8	51.6
		1.0	35.3	51.3	56.9	61.1	60.0	67.7	63.9	53.7	57.3	63.1
	6	0.5	42.6	55.2	58.4	67.4	62.7	68.0	61.0	58.5	63.3	57.3
		1.0	43.2	55.6	58.3	63.2	61.0	67.9	56.2	57.2	55.6	63.7
	7	0.5	43.2	51.9	57.6	64.0	65.0	69.0	62.2	60.4	61.5	58.1
		1.0	42.5	51.2	57.7	58.3	64.7	70.5	50.0	54.0	62.2	57.7
	8	0.5	40.5	54.0	56.5	65.5	66.3	69.9	60.0	60.5	59.6	56.9
		1.0	43.6	54.1	51.3	66.8	65.5	71.0	52.0	54.2	48.0	54.1
	9	0.5	68.2	50.2	61.0	63.7	65.4	71.2	63.0	60.8	60.1	52.2
		1.0	40.1	54.0	48.2	63.4	65.0	74.3	52.1	54.4	44.4	50.8
	10	0.5	44.2	52.1	54.4	65.4	66.0	72.5	65.0	60.1	50.8	55.5
		1.0	45.3	55.3	39.2	62.8	69.5	73.2	63.2	70.6	51.2	49.2
Mean			*41.4*	*50.1*	*56.8*	*63.6*	*63.2*	*65.6*	*63.5*	*61.7*	*60.2*	*52.4*
SD			*8.5*	*5.3*	*5.5*	*2.6*	*6.3*	*6.0*	*7.0*	*5.9*	*7.5*	*6.7*

Table A.14. MBT3 - Moisture content determinations (%, wet matter basis).

		Zone									
Sample	Replicate	1	2	3	4	5	6	7	8	9	10
1	1	50.7	46.6	52.8	51.0	41.5	47.0	46.6	34.0	25.2	22.6
	2	49.6	46.8	51.4	50.7	44.7	42.9	43.6	31.2	19.8	26.1
2	1	50.3	49.7	44.0	41.4	41.8	44.6	33.0	33.9	31.5	18.5
	2	47.1	48.9	44.4	43.1	41.1	44.5	30.7	38.3	31.6	17.4
3	1	49.7	45.6	49.1	45.2	37.7	37.6	42.2	36.1	27.7	25.3
	2	47.7	45.3	53.9	48.4	38.8	38.0	41.2	37.4	26.7	22.8
4	1	46.8	49.1	46.4	44.1	43.1	42.0	39.1	28.0	31.7	26.1
	2	50.6	47.8	44.7	43.5	45.1	38.8	40.4	29.1	33.3	31.1
5	1	49.0	49.6	44.5	34.5	41.1	39.2	38.9	31.5	22.8	33.3
	2	49.6	48.1	46.7	39.1	39.5	38.2	42.7	34.0	22.0	32.6
Mean		*49.1*	*47.8*	*47.8*	*44.1*	*41.4*	*41.3*	*39.8*	*33.3*	*27.2*	*25.6*
SD		*1.4*	*1.6*	*3.7*	*5.1*	*2.4*	*3.3*	*4.8*	*3.4*	*4.7*	*5.5*

Table A.15. MBT3 - Oxygen concentration measurements (%, v/v).

		Zone									
Day	Point	1	2	3	4	5	6	7	8	9	10
1	1	4.1	17.8	17.0	14.6	17.7	5.5	15.1	18.8	10.7	19.0
	2	1.5	18.6	18.3	18.2	18.4	17.1	13.0	19.4	18.9	18.7
	3	0.6	0.8	10.5	12.0	17.7	9.4	6.7	18.5	0.5	16.3
	4	0.8	0.1	14.0	13.4	16.9	16.8	3.2	18.6	18.1	19.1
	5	2.9	16.7	17.1	17.7	16.6	19.6	17.9	19.1	18.8	19.5
	6	3.8	0.3	17.0	8.4	17.2	0.7	2.4	11.9	4.6	19.5
Mean		*2.3*	*9.1*	*15.7*	*14.1*	*17.4*	*11.5*	*9.7*	*17.7*	*11.9*	*18.7*
SD		*1.5*	*9.5*	*2.9*	*3.7*	*0.6*	*7.5*	*6.5*	*2.9*	*8.0*	*1.2*

Table A.16. MBT3 - Total bulk density determinations (g/cm^3, wet matter basis).

	Zone									
Sample	1	2	3	4	5	6	7	8	9	10
1	0.88	0.73	0.54	0.78	0.62	0.73	0.74	0.72	0.61	0.63
2	0.86	0.76	0.72	0.69	0.60	0.65	0.63	0.68	0.66	0.56
3	0.86	0.73	0.75	0.74	0.57	0.69		0.61	0.64	0.57
4	0.73	0.76	0.71	0.68	0.65	0.62	0.69	0.56	0.64	0.63
5	0.80	0.71	0.70	0.59	0.72	0.57	0.71	0.60	0.63	0.71
Mean	*0.83*	*0.74*	*0.68*	*0.70*	*0.63*	*0.65*	*0.69*	*0.63*	*0.64*	*0.62*
SD	*0.06*	*0.02*	*0.08*	*0.07*	*0.06*	*0.06*	*0.04*	*0.06*	*0.02*	*0.06*

Table A.17. MBT3 - Free air space values (fractional) (calculated as explained in section 4.1.7).

	Zone									
Sample	1	2	3	4	5	6	7	8	9	10
1	0.34	0.46	0.61	0.45	0.57	0.49	0.49	0.53	0.63	0.62
2	0.36	0.43	0.47	0.51	0.58	0.54	0.57	0.56	0.60	0.66
3	0.35	0.46	0.45	0.47	0.60	0.52		0.60	0.61	0.66
4	0.45	0.44	0.48	0.51	0.54	0.57	0.53	0.63	0.60	0.62
5	0.40	0.48	0.49	0.58	0.49	0.61	0.51	0.61	0.61	0.57
Mean	*0.38*	*0.45*	*0.50*	*0.50*	*0.56*	*0.55*	*0.53*	*0.59*	*0.61*	*0.63*
SD	*0.05*	*0.02*	*0.06*	*0.05*	*0.04*	*0.04*	*0.03*	*0.04*	*0.01*	*0.04*

Table A.18. MBT3 - Volatile solids content determinations (%, dry matter basis).

		Zone									
Sample	Replicate	1	2	3	4	5	6	7	8	9	10
1	1	47.8	47.2	41.0	37.5	41.3	37.0	39.4	31.1	33.3	29.0
	2	41.3	44.0	38.2	36.7	42.6	35.1	35.1	25.5	25.9	28.7
2	1	48.6	50.4	41.0	39.4	43.6	36.7	38.1	33.2	32.6	28.9
	2	46.4	45.4	40.9	39.0	40.0	41.6	29.5	38.0	37.9	28.5
3	1	45.6	40.2	42.4	38.1	41.1	39.0	33.9	33.6	27.9	38.3
	2	46.2	43.9	30.3	39.7	43.7	32.5	29.0	33.9	26.3	28.4
4	1	40.4	43.9	41.1	37.1	36.0	38.7	33.5	34.7	29.8	26.6
	2	44.5	41.5	39.4	39.8	39.8	30.9	36.0	32.1	33.7	31.5
5	1	61.0	45.3	34.0	33.7	40.4	41.0	36.8	35.8	25.8	32.7
	2	58.1	42.4	37.7	34.6	40.2	37.4	37.0	37.4	27.5	30.1
Mean		*48.0*	*44.4*	*38.6*	*37.6*	*40.9*	*37.0*	*34.8*	*33.5*	*30.1*	*30.3*
SD		*6.6*	*2.9*	*3.8*	*2.1*	*2.2*	*3.4*	*3.4*	*3.6*	*4.1*	*3.3*

A.4 MBT4

Table A.19. MBT4 - Temperature measurements (ºC). All measurements made at the depth of 1.0 meter. (To be continued)

		Zone					
Day	Point	1	2	3	4	5	6
1	1	47.8					
	2	46.8					
	3	43.1					
	4	46.9					
	5	46.0					
	6	48.7					
	7	46.7					
	8	45.8					
	9	48.7					
2	1	32.6		51.7	69.6	73.7	
	2	17.8		50.9	72.8	75.6	
	3	33.6		51.1	70.4	74.9	
	4	41.0					
	5	40.4					
	6	36.3					
	7	37.0		48.5	63.5	75.0	
	8	28.2		50.0	66.6	75.0	
	9	37.7		49.0	65.5	74.8	
3	1			69.8	71.2	58.7	
	2			72.3	71.4	72.1	
	3			70.6	66.8	62.5	
	4						
	5						
	6						
	7			63.9	70.4	61.9	
	8			67.4	64.3	66.2	
	9			51.9	64.2	32.0	
4	1	27.9	47.0		57.8	64.2	72.8
	2	29.4	46.4		62.1	65.4	75.0
	3	28.4	48.2		59.4	65.0	73.9
	4		38.5				
	5		54.0				
	6		45.2				
	7	29.7	50.0		49.8	59.3	73.6
	8	33.5	50.2		55.9	62.4	75.4
	9	29.8	49.8		54.1	61.2	74.8
5	1	43.1			60.5	74.5	61.7
	2	36.2			65.1	75.3	75.6
	3	38.4			65.6	73.1	48.3
	4						
	5						
	6						
	7	40.9			67.5	75.2	43.4
	8	33.3			65.8	74.6	67.8
	9	35.4			60.7	73.8	32.2

Table A.19. MBT4 - Temperature measurements (ºC). All measurements made at the depth of 1.0 meter. (Continuation)

		Zone					
Day	Point	1	2	3	4	5	6
6	1	23.2	50.7	43.5			58.2
	2	27.4	50.9	51.9			58.3
	3	22.4	53.1	40.0			55.7
	4			48.9			
	5			54.2			
	6			39.4			
	7	24.1	52.5	47.4			61.2
	8	23.1	51.2	51.8			60.1
	9	23.3	50.9	44.8			61.3
7	1	32.5	55.7	45.2		64.4	69.5
	2	34.8	54.6	52.8		63.5	73.9
	3	29.1	53.7	34.8		64.9	59.8
	4			59.8			
	5			66.3			
	6			39.1			
	7	30.5	56.4	47.6		63.8	73.0
	8	36.3	58.4	51.4		65.5	76.7
	9	38.9	60.0	43.1		71.1	67.2
8	1	30.8	57.9		70.5		67.7
	2	31.7	57.0		74.8		64.9
	3	35.6	55.6		69.3		62.8
	4				52.6		
	5				62.4		
	6				39.2		
	7	25.3	54.8		70.1		63.7
	8	25.0	57.9		72.0		64.4
	9	25.6	61.0		64.8		60.6
9	1	31.8	61.5		63.9	63.3	72.9
	2	32.1	62.1		62.8	61.9	72.5
	3	40.5	64.0		61.4	62.9	69.6
	4					68.1	
	5					71.1	
	6					68.8	
	7	45.6	65.0		61.6	65.7	69.5
	8	43.1	66.8		58.5	66.2	72.9
	9	45.9	63.4		60.5	64.8	70.5
10	1	29.2	42.0	55.6	68.6	69.0	
	2	30.4	41.9	55.8	67.1	67.5	
	3	30.0	42.1	54.9	65.9	71.7	
	4					55.0	
	5					67.2	
	6					64.2	
	7	28.7	42.8	58.3	67.6	72.8	
	8	28.0	42.9	61.0	66.2	72.8	
	9	30.0	43.3	62.8	61.5	70.0	

Table A.19. MBT4 - Temperature measurements (ºC). All measurements made at the depth of 1.0 meter. (Continuation)

		Zone					
Day	Point	1	2	3	4	5	6
11	1	37.6	52.1			66.4	74.5
	2	43.9	51.4			64.0	73.0
	3	33.8	49.9			65.5	70.0
	4						36.5
	5						65.0
	6						45.0
	7	36.0	54.5			60.6	75.1
	8	38.0	53.6			63.7	74.2
	9	38.1	54.0			63.2	74.5
12	1		43.0	59.0		65.0	
	2		44.0	62.0		69.0	
	3		45.0	70.0		66.0	
	4		51.0	64.0		61.0	
	5		51.0	68.0		64.0	
	6		49.0	65.0		56.0	
	7		45.0	59.0		47.0	
	8		48.0	62.0		58.0	
	9		46.0	54.0		46.0	
13	1		31.0		41.0	46.0	59.0
	2		33.0		41.0	46.0	54.0
	3		31.0		41.0	49.0	54.0
	4		31.0		36.0	49.0	59.0
	5		33.0		39.0	49.0	62.0
	6		32.0		38.0	52.0	57.0
	7		32.0		31.0	46.0	51.0
	8		32.0		31.0	46.0	63.0
	9		33.0		31.0	54.0	57.0
14	1	32.0	39.0	39.0	39.0		50.0
	2	24.0	43.0	43.0	40.0		52.0
	3	31.0	41.0	41.0	33.0		51.0
	4	34.0	45.0	45.0	59.0		50.0
	5	23.0	47.0	47.0	55.0		50.0
	6	36.0	38.0	38.0	60.0		52.0
	7	22.0	38.0	38.0	26.0		44.0
	8	22.0	39.0	39.0	35.0		47.0
	9	22.0	23.0	23.0	25.0		45.0
15	1		35.0	33.0	47.0	49.0	73.0
	2		34.0	35.0	46.0	50.0	72.0
	3						
	4		33.0	35.0	47.0	63.0	71.0
	5		35.0	33.0	48.0	61.0	69.0
	6						
	7		34.0	31.0	49.0	53.0	61.0
	8		32.0	30.0	47.0	55.0	62.0
	9						
Mean		*33.9*	*46.7*	*50.3*	*56.0*	*62.9*	*62.5*
SD		*7.8*	*9.9*	*11.8*	*13.4*	*9.2*	*10.7*

Table A.20. MBT4 - Moisture content determinations (%, wet matter basis).

			Zone					
Day	Sample	Replicate	1	2	3	4	5	6
1	1	1	54.5		39.5			53.6
		2	51.3		49.8			39.6
	2	1	52.9		53.0			35.4
		2	53.8		50.2			36.6
	3	1	53.5		53.0			47.5
		2	53.2		54.3			41.8
2	1	1	58.9	54.2	61.1		49.3	45.9
		2	55.2	59.1	52.5		46.0	46.2
	2	1	54.5	56.1	56.1		46.5	43.0
		2	54.2	60.3	54.8		49.9	43.5
	3	1	55.9	58.1	50.5		45.6	42.7
		2	48.4	54.4	50.5		45.0	41.9
	4	1	59.1	57.1	59.7		54.4	44.8
		2	59.2	56.0	56.5		55.7	44.5
	5	1	56.7	59.1	55.2		38.7	40.6
		2	57.5	56.7	52.8		40.2	33.8
	6	1	62.4	55.1	55.5		57.8	41.2
		2	56.5	55.7	58.9		58.2	38.7
Mean			*55.4*	*56.8*	*53.5*		*48.9*	*42.3*
SD			*3.3*	*2.0*	*4.8*		*6.5*	*4.7*

Table A.21. MBT4 - Oxygen concentration measurements (%, v/v).

		Zone					
Day	Point	1	2	3	4	5	6
1	1	3.2	19.3		0.1	5.6	17.0
	2	2.8	18.0		0.1	4.9	17.2
	3	4.3	17.7		0.1	5.6	17.1
	4	3.0	13.3		0.1	4.0	18.0
	5	4.6	13.7		0.3	8.9	12.9
	6	0.4	14.8		0.0	12.0	16.7
	7	1.1					
	8	1.9					
	9	1.6					
2	1	0.0	0.2	15.3	8.2		7.6
	2	0.4	0.0	14.8	5.0		5.9
	3	0.1	0.0	17.6			5.7
3	1	8.0	0.0	19.8	19.8	18.7	15.9
	2	6.8	0.0	19.7	19.9	17.3	14.5
	3	6.0	2.7	19.3	18.7	16.1	12.4
	4	0.5	0.0	20.0	20.0	15.8	15.2
	5	7.9	1.4	18.7	19.3	16.6	4.3
	6	19.7	0.0	19.8	19.0	15.5	7.8
4	1	19.2	14.7	12.2		19.9	
	2	19.1	8.8	1.3		5.5	
	3	17.4	6.4	0.8		16.7	
	4	17.4	12.6	0.6		10.2	
	5	19.2	0.6	5.5		11.7	
	6	17.5	0.5	10.2		10.2	
	7	13.4	0.5	0.4		6.7	
	8	16.0	0.5	17.5		10.1	
	9	15.8	1.2	17.8		12.7	
	10	16.5	2.2	18.1		11.8	
5	1	18.2	11.2	12.7		18.9	
	2	16.9	12.7	11.7		18.5	
	3	16.9	10.6	8.2		18.9	
	4	12.5	12.8	3.7		17.7	
	5	16.8	0.0	5.6		17.0	
	6	15.4	0.0	1.3		16.8	
	7	16.5	0.0	8.8		16.5	
	8	3.9	2.3	17.9		16.1	
	9	15.1	0.5	18.1		17.6	
	10	10.4	5.8	18.4		18.0	
Mean		*10.2*	*5.9*	*12.3*	*9.3*	*13.5*	*12.5*
SD		*7.2*	*6.7*	*7.1*	*9.4*	*4.9*	*4.9*

Table A.22. MBT4 - Total bulk density determinations (g/cm^3, wet matter basis).

	Zone					
Sample	1	2	3	4	5	6
1	0.69	0.70	0.65	0.70		0.74
2	0.62	0.74	0.70	0.71		0.68
3	0.55	0.72	0.72	0.72		0.73
4	0.57	0.76	0.64			
5	0.59	0.75	0.64			
Mean	*0.61*	*0.73*	*0.67*	*0.71*		*0.72*
SD	*0.06*	*0.02*	*0.04*	*0.01*		*0.03*

Table A.23. MBT4 - Free air space values (fractional) (calculated as explained in section 4.1.7).

	Zone					
Sample	1	2	3	4	5	6
1	0.46	0.45	0.50	0.47		0.48
2	0.52	0.41	0.46	0.46		0.52
3	0.57	0.43	0.44	0.45		0.48
4	0.55	0.40	0.51			
5	0.54	0.41	0.51			
Mean	*0.53*	*0.42*	*0.48*	*0.46*		*0.49*
SD	*0.04*	*0.02*	*0.03*	*0.01*		*0.02*

Table A.24. MBT4 - Volatile solids content determinations (%, dry matter basis).

			Zone					
Day	Sample	Replicate	1	2	3	4	5	6
1	1	1	46.7		60.4			
		2	42.7		42.5			38.2
	2	1	46.1		50.7			38.7
		2	43.1		42.4			39.6
	3	1	52.2		45.9			50.2
		2	49.8		47.2			38.4
2	1	1	45.8	44.3			42.8	38.4
		2	47.8	51.5	36.0		40.4	39.4
	2	1	41.7	46.2	48.8		43.8	38.0
		2	44.1	55.2	43.4		47.2	42.1
	3	1	44.5	51.7	47.9		38.9	38.1
		2	29.6	39.5	48.0		43.1	35.9
	4	1	43.6	47.6	50.5		45.7	45.0
		2	43.3	50.8	43.6		45.8	40.7
	5	1	40.7	59.9	50.8		41.0	39.8
		2	47.3	50.4	44.9		43.3	36.6
	6	1	51.3	49.2	39.1		40.8	37.5
		2	45.0	44.7	41.9		41.3	35.1
Mean			*44.7*	*49.3*	*46.1*		*42.9*	*39.5*
SD			*4.9*	*5.4*	*5.6*		*2.5*	*3.6*